AIRS Instrument Calibration Plan

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AIRS Calibration Plan Outline

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1. Introduction

1.1. Overview

AIRS is a key facility instrument scheduled for launch in the December 2000 on NASA's second of several Earth Observing System (EOS) platforms. It will be placed into a 705 km altitude polar, sun synchronous orbit. EOS is a global observation system designed to obtain comprehensive long-term measurements of Earth processes affecting global change. The role of AIRS will be to provide infrared spectral data about the atmosphere, land and oceans, with nearly continuous coverage in the mid and long wave IR and with greater accuracy than provided by currently deployed instruments, for application to climate studies and weather prediction. Among the important parameters to be derived from AIRS observations are atmospheric temperature profiles, ocean and land surface temperatures, humidity profiles and total precipitable water vapor, and cloud fractional coverage and properties.

The AIRS measurement technique is based on passive remote sensing, employing a high spectral resolution nadir-viewing spectrometer to operate over the 3.7µm to 15.4 µm region. The instrument is a cooled, multi-aperture Echelle grating spectrometer that provides spectral multiplex operation (all wavelengths measured simultaneously). The complete spectrum is dispersed over a number of linear infrared detector arrays which are cooled to cryogenic temperature using a mechanical refrigerator. Figure 1.1 shows the AIRS instrument layout. In addition to the IR spectrometer, the AIRS includes four visible/near IR channels designed primarily to provide diagnostic support for the temperature and moisture sounding.

Calibration of AIRS is vitally important to its intended mission, since the quality of the calibration corresponds directly to the quality of the data obtained. AIRS is the latest in a series of increasingly accurate and versatile satellite-borne atmospheric sounders, and its calibrations must consequently be better than the system it is intended to replace.

The following AIRS pre-launch instrument calibration tasks are instrument contractor responsibilities:

(1) Design, develop, fabricate, test, calibrate and integrate in-flight calibration subassemblies;
(2) Develop AIRS instrument models and analytical tools in support of calibration tasks;
(3) Design, develop, fabricate, integrate, test, and calibrate AIRS program specific Ground Support Equipment (GSE); including Bench Checkout Equipment (BCE), the critical AIRS Test and Calibration Facility (ATCF) and the Ground Support Station (GSS);
(4) Perform critical subassembly pre-flight characterizations and calibrations with the BCE, providing flight-inaccessible parameter measurements and documentation;
(5) Perform and document pre-flight AIRS instrument calibrations using the ATCF.

The following tasks are AIRS Science team member/TLSCF responsibilities:
(1) Develop flight calibration algorithms;
(2) Pre-launch end-to-end instrument performance validation;
(3) Reconciliation of instrument abnormalities with additional analysis of preflight test data;
(4) Radiometric, photometric and spectral validation of the level 1b radiances;
(5) Cross-validation of radiances with other instruments on the spacecraft.

The division of responsibility between the instrument contractor and the AIRS science team in the area of pre-launch calibration data analysis, pre-launch instrument performance validation and in-orbit performance validation is clarified in Table 1.1.

Table 1. AIRS Calibration / Validation

Lockheed/Martin Responsibility				AIRS Science Team Responsibility				
	PARAMETER	MEASUREMENT APPROACH	CALIBRATION	INSTRUMENT PERFORMANCE VALIDATION	PRODUCT VALIDATION	Task	PreLaunch	PostLaunch
1	Scene Dynamic Range	Sweep LABB over dynamic range	Demonstrated FRD compliance		1	Spectroscopic Validation	Laboratory Work, Field Campaigns (intermittent)	Laboratory Work, Field Campaigns (intermittent)
	Radiometric Calibration Accuracy	Same test as above	FRD compliance proven by analysis	Curve fit for non-linearity correction	2	Forward Model Validation	Improve the physics and field test results	Field Campaigns (intermittent)
2	Scan Response Uniformity	LABB at 300K and 250K all angles from ±50 degrees	Demonstrated FRD compliance	Validate that NEN is not scan angle dependent	3	Field Campaign Studies	Data set preparation, development of plans, instrument monitoring	Data set preparation, development of plans, instrument monitoring
3	Sensitivity (NEDT)	LABB at 220K, 250K, 300K and 340K	Characterize rms noise at full dynamic range. Characterize 1/f noise (if any)	Indirect validation during the 24 hour test.	4	Long term Intercomparison	Code development	Radiosonde collocation and analysis. (long term)
4	Spectral Coverage, SRF centroid and Resolution	FT-Interferometer. Optimize for spectral resolution.	Acceptance test to demonstrated FRD compliance		5	Algorithm Error Characterization	Simulation system development	Maintenance
	SRF low level wing response	FT-Interferometer. Optimize analysis for SNR	Characterizes SRF at all wavelength with more than 1/3000 of peak response	Evaluate retrieval error if not FRD compliant Validate grating model for spectral calibration Validate non-linearity correction based on ghost suppression	6	Radiance validation	Code development	Long term trend monitoring, Vicarious radiance validation (intermittent). Cross validation with other instruments. (intermittent)
5	Wavelength Calibration stability in 24 hours	24 hours test with gas-cell at nadir position	Demonstrate FRD compliance	Validate spectral calibration algorithm. Validate frequency tracking algorithm	7	Geophysical parameter validation	Assess error characteristics of InSitu data sources	InSitu assessment, cross validation with other instruments, model verification (long term)
6	Spatial Response IFOV FWHM 99% of power 99.5% of power	<0.5 degree pointsource in azimuth and elevation	Demonstrate FRD compliance	Use for cross-calibration	8	Model Assimilation	Development of AIRS specific assimilation	Impact assessment of AIRS data
7	Measurement Simultaneity	<0.5 degree point source rasterscan in 1.5 degree diameter field	Calculate Cij from spatial response test	Optimize cloud clearing channels for measured Cij	9	Validation Data System Development	Data Warehouse development, analysis software development	Maintenance
8	Instrumental Polarization	Wiregrid polarizer at 0, 45 and 90 degree	Measure polarization and principal axis at all wavelengths	Validate polarization correction equation				
9	Spectral centroid, resolution and absolute calibration	Low pressure gas cell		Compare with calculated gas absorption depth and positions				
10	end-to-end pre-launch system test	Vertical look through earth atmosphere at night and day		Compare with uplooking AERI interferometer and fast-code				

1. 2. Purpose

The purpose of the Calibration Plan is to provide a single reasonably detailed, up-to-date source of information on the calibration of the AIRS instrument for the user of the AIRS data. This includes discussion of the philosophy and approach to the calibrations and the role of the instrument contractor, the AIRS science team members and the AIRS data processing team in various phases of the pre-flight and in-flight calibration. It includes descriptions of the internal flight instrument calibrators and the external ground support facilities. It discusses modeling employed in support of calibration, key calibration algorithms and the validation of all calibrations performed.

1.3. Scope

This plan principally covers high level aspects of the AIRS calibration, i.e. the determination of those parameters which either
a) enter explicitly in the algorithms which accomplish the conversion from Level 1a (data numbers) to Level 1b (spectral radiances), such as the use of the temperature sensors in establishing the output of the black-body,
    or
b) enter indirectly into the data processing, such as the detailed shape of the SRF and location of the centroids of the SRF in the pre-calculated retrieval weighting functions,
    or
c) enter implicitly into the quality of the data, such as measurement simultaneity, noise and dynamic range, and are as such specified in the Functional Requirements Document (FRD).

This plan does not address the details of actual procedures to be used (the "Test Plan") or details of the ground-calibration software. The AIRS Level 1b ATBD (Algorithm theoretical Basis Document) (current Version 1.1. 15 November 1996) discusses the algorithmic and flowchart description of the procedures which convert the data numbers received on the ground (Level 1 data) to calibrated spectral radiances (Level 1b products). Details of the pre-launch and post-launch validation effort are presented in the AIRS Validation Plan, submitted to the EOS project office at GSFC on August 15, 1997.

1.4. Calibration Philosophy

Both ground-based and in-flight calibrations of the AIRS instrument include radiometric, photometric, spectral and spatial calibrations. We distinguish between direct calibration, relative to accessible secondary or tertiary physical standards, and indirect (remote or vicarious) calibration, relative to geophysical sources such as characterized ocean or desert regions and the network of radiosonde instruments constantly deployed.

The AIRS radiometric calibration, with the exception of the Vis/NIR channels, involves pre-flight calibrations relative to secondary standards traceable to the National Institute of Standards and Technology (NIST) and in-flight internal calibrations relative to the secondary standards. The infrared radiometric calibration depends totally on the prelaunch characterization of the flight calibration black-body and the electronic transfer functions.

The AIRS spectral calibration, i.e. knowledge of the shape and centroid of the spectral response functions (SRF), uses a commercial, high resolution Fourier Transform Infrared Spectrometer (FT-IR), corroborated with laboratory gas spectroscopic standards. The in-flight calibration of the SRF centroids is based on the combination of spectrally resolved features in the upwelling spectral radiances with the accurate pre-launch characterization

of the focal plane. For the knowledge of the SRF shapes AIRS relies on the accurate pre-launch characterization and stability of the spectrometer.

The AIRS Vis/NIR channels use vicarious calibration, i.e. the upwelling radiation from characterized regions of the ground and cross-calibration with the MODIS instrument, to achieve absolute calibration. No pre-flight absolute calibration is required. The pre-flight photometric measurements of the Vis/NIR channels using a commercially available, NIST traceable, filter photometer, verify the stability and the brightness of the in-flight photometric reference source.

The pre-flight spatial calibrations are based on standard metrical techniques, with precision alignment and X-Y spot scans of the instrument's field of view.

The routine monitoring of the radiometric, spectral and spatial calibrations of the AIRS instrument relative to geophysical sources is part of data product validation.

1.5. Instrument Description

Figure 1.1 shows a cut-away overview of the AIRS instrument. The heart of the AIRS system is the IR Sensor Assembly which contains an eleven aperture, Echelle grating spectrometer. The eleven apertures define the entrance slits of the spectrometer, which are spectrally dispersed by the grating. Each slit maps into one or two arrays in the focal plane. To maximize sensitivity, the IR Spectrometer Assembly is cooled to 155 K using a two-stage passive radiative cooler. The focal plane arrays include both photovoltaic and photoconductive mercury cadmium telluride (HgCdTe) detectors cooled to 60 K utilizing pulse tube mechanical refrigerators specially developed for long-life space operation.
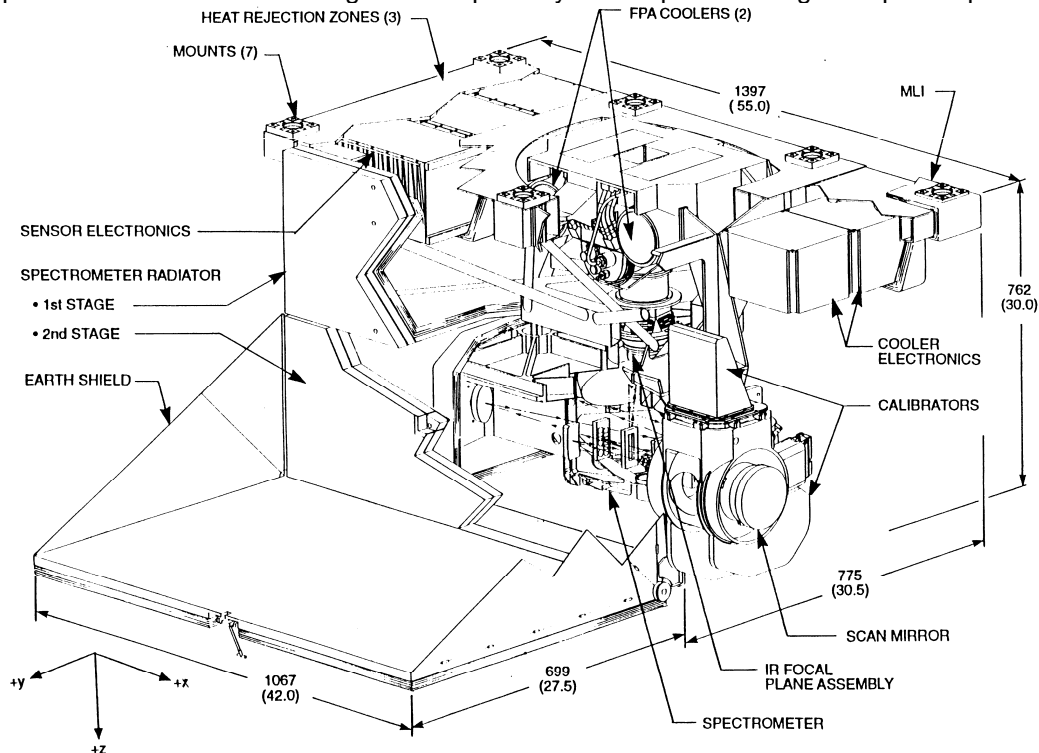

Figure 1.1 Cut-away overview of the AIRS instrument. The heart of the AIRS system is the IR Sensor Assembly which contains a multi-aperture, echelle grating spectrometer and corresponding multiple detector arrays.

The schematic layout of the entrance slits and the corresponding detector arrays is shown in Figure 1.2. Spectral coverage is provided from 3.74µm to 4.61 µm, 6.20 µm to 8.22 µm,

and 8.80 µm to 15.4 µm with 2500 spectral channels arranged in 12 linear arrays. Within each array the detectors are arranged with a 50 micron pitch in the dispersed direction.
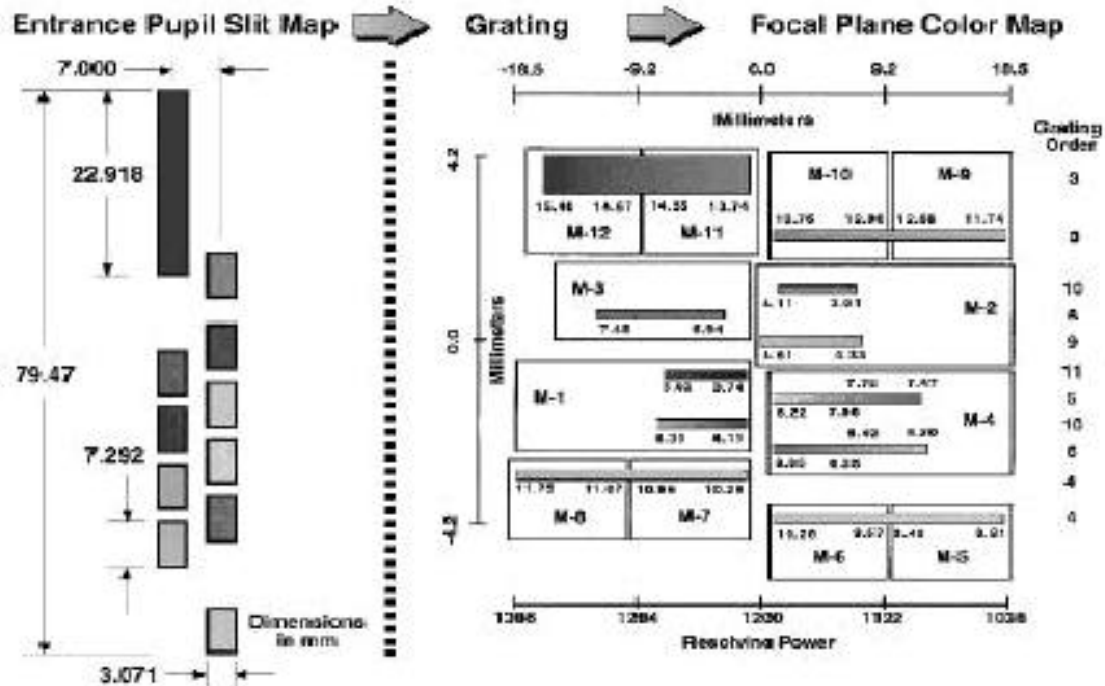

Figure 1.2. Mapping of the eleven entrance apertures pupils into the focal plane arrays. Each array has a order isolation filter.
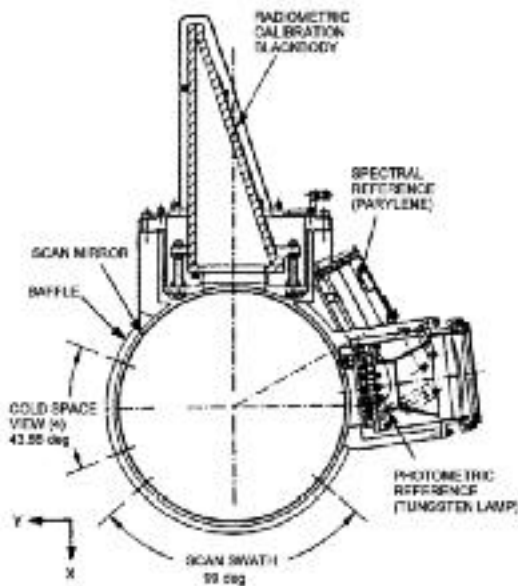

Figure 1.3. Cross-section of the scan head assembly shows key calibration elements.

The IR Spectrometer Assembly includes a pupil imaging telescope which views the Earth and calibrator assemblies through a rotating scan mirror in the scan head assembly. In the cross-track direction, a ±49.5 degree swath centered on the nadir is scanned in 2 seconds, followed by a rapid scan in 2/3 second covering four views of space, the on-board radiometric calibration blackbody, the spectral reference source and the photometric reference source. While in-flight calibration measurements are made once per scan line (every 2.667 seconds), data from ten or more scan lines are combined by the ground calibration software to update calibration coefficients.

A single aperture in the image plane defines the spatial field of view at all wavelengths. This design virtually assures that all wavelength measure the same spot on the ground at

the same time. However, the design has the drawback that the entrance pupil is not circular, but looks like the projection of the eleven individual apertures.
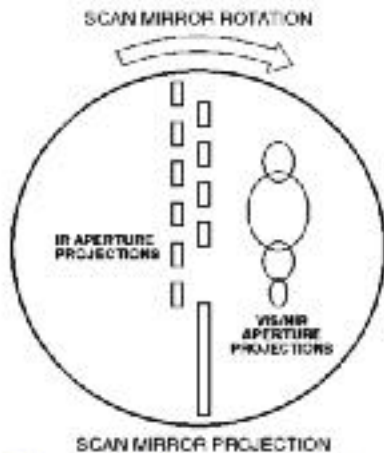

Figure 1.4 Aperture projections on scan mirror

As the scan mirror rotates to point the spectrometer field-of-view to the scene, the calibration sources or the space views, the projections of the entrance apertures trace out concentric arcs on the surface of the scan mirror. The scan mirror temperature is 255K at the start of the mission, increasing to 263K after 5 years in orbit. Because of the low scan mirror temperature the aperture projection has no impact on the radiometric calibration. This is discussed in the section 2.4.2.1. under "scan response uniformity". The scan mirror temperature is monitored by a non-contacting temperature sensor.
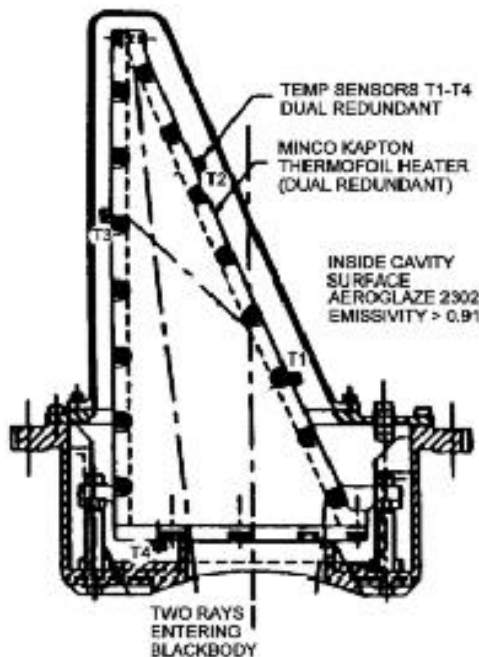

Figure 1.5.a. Cross-section of the in-flight radiometric calibrator assembly.

Figure 1.5.a shows a vertical cross-section of the in-flight radiometric calibrator assembly, including the location of four temperature sensors. The radiometric calibrator employs a deep wedge-shaped cavity (2:1 depth to width ratio) with 27.25 degree wedge angle and with a rectangular clear aperture of 5.7 x 9.5 cm. The black-body temperature is controlled at 308K using tape heaters. Temperature uniformity of the radiating surfaces is expected to be 0.07K.

The two extreme rays (dash-dot lines) in the drawing show the multiple reflections achieved with a wedge cavity design. The radiating surface is coated specular black to achieve an effective and end-of-life emissivity of $\cong 0.993$.
Four dual redundant temperature sensors (T1 - T4) measure the temperature at key positions of the cavity surface to an accuracy of 0.1K each. A linear combination of the temperatures measured by sensors T1 through T4 is used calculate the spectral radiance emitted by the calibrator during the ground processing of the flight data.

Views of the flight blackbody and the cold space view provide a two-point radiometric calibration for gain measurement and for background signal and electrical offset correction. The radiometric accuracy of the AIRS instrument depends directly on the accuracy of its flight calibration source and the quality of the cold space view. The radiance output from the flight blackbody is a function of the source temperature and the effective emissivity. The AIRS design uses thermistor thermometers and very low drift and

low noise monitoring circuitry. The effects of surface emissivity changes have been reduced to negligible amounts using the wedge cavity design.
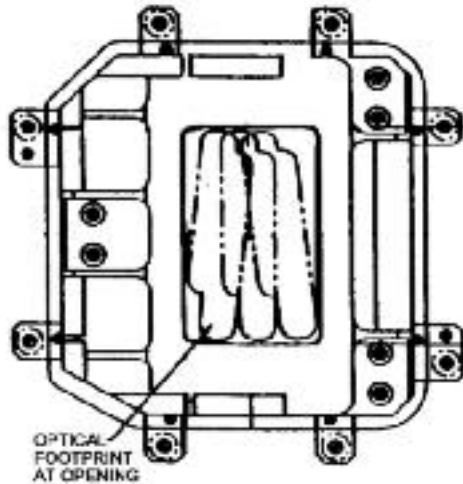

The spectrometer entrance apertures are projected into the opening of the blackbody cavity. The scan mirror continues to rotate while the infrared detectors view the blackbody cavity. The outline of the optical footprint at the cavity opening at the start, the middle and the end of the dwell time is shown looking ("up") into the wedge cavity in Figure 1.5.b. The selection of the precise timing of the calibration dwell time is part of the radiometric calibration.

Figure 1.5.b. I.R. entrance aperture beam projection into the opening of the blackbody assembly.

The space view port provides a four degree cone, centered on the 1.1 degree AIRS FOV, clear of physical obstructions for four consecutive space views.

The primary spectral calibration of the AIRS spectrometer is based on the cross-correlation between spectral features observed in the upwelling radiance spectrum with precalculated spectra, discussed in more detail in section 2.5.2. An additional spectral reference source is provided to aid pre-launch testing in the thermal vacuum chamber during spacecraft integration and for quality monitoring in orbit.
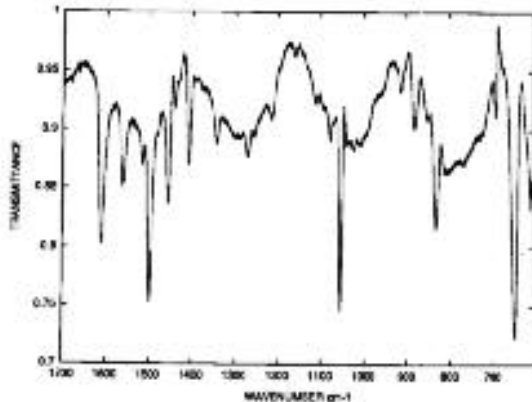
This additional source is a gold-coated concave mirror at instrument temperature (about 300K), with a vapor deposited overcoat of a 12 micron thick layer of Parylene C. Parylene C is commonly used in space applications for conformal coating of electronics boards. Figure 1.6 shows a transmission spectrum of Parylene C measured with 0.2cm-1 resolution. The "sharp" spectral features are actually 3-5 cm-1 wide. The spectrum observed will be the emission spectrum of Parylene C at 300K, with an estimated SNR in excess of 100 from a single observation. Four broad spectral features allow the position of four of the 12 arrays in the AIRS focal plane to be located with a precision of 0.03*FWHM using a single observation.

Fig. 1.6. Transmission spectrum of Parylene C

 Also included as part of the AIRS instrument is the Vis/NIR Sensor Assembly employing four channels, with spectral coverage from 0.40-44 μm, 0.58-0.68 μm, 0.71-0.96 μm, and 0.45-0.95 μm. The Vis/NIR channels, which have nominally six times the spatial resolution of the IR Sensor Assembly, are implemented with four optically co-aligned linear 1 x 9 element arrays, which are swept push-broom fashion along the in-scan (cross-track) direction by the Scan Assembly. The array elements are simultaneously sampled 8 times for each IR

dwell time. Each IR spectrometer footprint is thus overlayed with a grid of 9x8 visible detector pixels in four wavelength channels between 0.4 and 1.0μm. The Vis/NIR Sensor Assembly is located within the Scan Head Assembly and shares the scan mirror with the spectrometer. As the scan mirror rotates the four entrance apertures sweep out concentric arcs. (Figure 1.7.a)
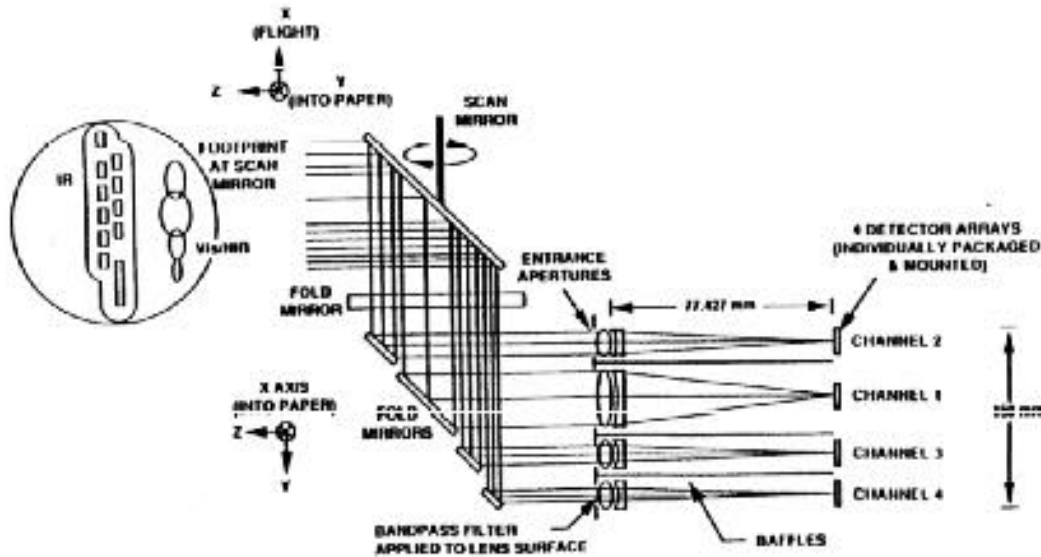
Fig.1.7.a. **Schematic of the optical layout of the Vis/NIR channels**

While the four Vis/NIR channels are optically 1 x 9 element arrays, each optical pixel being 250μm square, the pixel is electrically synthezised by adding the output of 10 sub-elements, each 25μm wide and 250μm long.

Equivalent sub-elements in each array are sampled simultaneously. The resulting trapezoidal skewing of the FOV due to the scan mirror rotation and the geometrical pixel geolocation algorithms are discussed in the Level 1b ATBD and JPL Document ADF-265.

Fig. 1.7.b. Vis/NIR detector layout
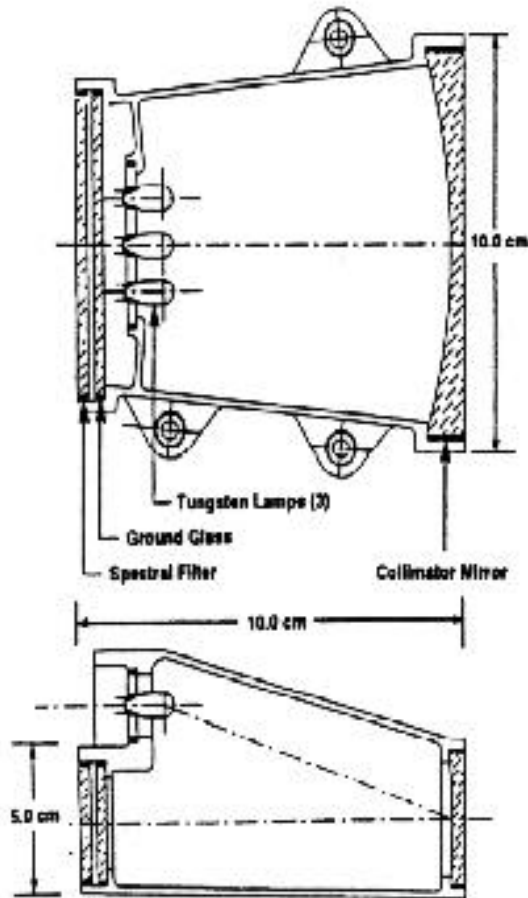
The photometric reference (Figure 1.8) for the Vis/NIR bands employs triple redundant tungsten lamps (Welch Allyn No. 01178), which back illuminate a ground glass screen. A spectral balancing filter adjusts the response in each of its four bands to approximately the same level (by enhancing the blue output of the lamp). The collimating mirror in the calibrator conserves lamp power. Each calibrator assembly is viewed by the instrument once each scan cycle (2.67 sec.). The Vis/NIR sensors use the view of the IR calibrator for a dark (zero signal) view. (The "cold space view" employed by the IR sensors is not a reliable zero signal for the visible sensors because of the potential of scattering from contaminants accumulated on external baffles which define the cold space view.) Calibrator lamp #1 is turned on for about 120 seconds once every orbit for the routine calibration. This is equivalent to 860 hours in five years. Calibrator lamp #2 is operated for 120 seconds once every day, and calibrator lamp #3 is operated for 120 seconds once each month. The software monitors the relative signal from the lamps to account for aging effects. When bulb #1 fails, lamp #2 is commanded for the routine calibration. The lamps are rated at 5.0 Volts, 0.44A, for a lifetime of 1200 hours at a color temperature of 2925K. For an extra margin of safety, the lamps are operated at 4.5V, 0.42A. The SNR for a single look at the calibration source is expected to be 45, 420, 960, and 500, for the channels 1 through 4, respectively.

Fig. 1.8. Vis/NIR Photometric Reference

On-board signal processing capability within the AIRS instrument is limited in order to preserve the raw science content of the data. Signals from each IR spectral sample and the Vis/NIR channels are digitized and formatted for output. The HcCdTe photovoltaic detector signal chain includes a software deglitcher to eliminate signal spikes due to the natural electron and proton radiation environment in orbit. Full data transmission, including science and housekeeping data, will be at approximately 1.31 Mb/s.

1.6. Reference Documents

The following documents are implicitly referenced in this plan.
(a) JPL Documents

D-6665	AIRS Science and Measurement Requirements	(September 1990)
D-7231	AIRS Science Management Plan	(September 1990)
D-7239	AIRS Data Management Plan	(August 1990)
D-7237	AIRS Calibration Management Plan	(December 1990)
D-8236	AIRS Functional Requirements Document	(January 1997)

(b) Lockheed Martin Documents

	Calibration Implementation Study Report	(August 1992)
SE001	Performance Verification Plan	(latest rev.)
SE009	Instrument Calibration Management Plan	(September 1994)
	Data reduction algorithm for the measurement	
	of the AIRS polarization", by George Gigiolo	(April 28, 1997).

(c) AIRS Science Team Documents

AIRS Level 1b Algorithm Theoretical Basis Document	
Version 1.1.	(16 November 1996)
AIRS Validation Plan,	
submitted to the EOS project office at GSFC	(15 August 1997)
AIRS Vis/NIR Geolocation Algorithm	
JPL Document ADF-265	(25 June 1997)

(d) Publications related to calibration:

H. Aumann and Ken Overoye "The Atmospheric Infrared Sounder (AIRS) on the Earth Observing System: In-orbit Radiometric and Spectral Calibration", Proceedings of the 10th Annual International Aerosense Symposium (SPIE) 8 April 1996, Orlando, Florida.

P.F.W. van Delst, H. E. Revercomb, R.O. Knuteson, H. H. Aumann and Ken Overoye "Simulations of AIRS spectral response function measurements with an FTS". Proceedings of the July 1997 SPIE Meeting in San Diego, CA.

2. Calibration Implementation

The calibration implementation of AIRS must be addressed in terms of

a)   the flow-down of the calibration requirements from the FRD,

b)   the physical standards with qualities of accuracy (through appropriate traceability to primary standards),

c) the required precision (including repeatability and stability) and resolution.

2.1. Calibration Requirements

2.1.1. Infrared Spectrometer Calibration.

1. Radiometric Calibration

The most critical calibrations are concerned with the system radiometric accuracy (specified in the FRD as < 3% of the signal or 4*NEN, whichever is greater), response function (offset, gain, and linearity) and stability of the in-flight calibrated AIRS system.

The AIRS spectrometer transmission is polarization dependent. The FRD limits the permissible amount of instrumental polarization to 25% at wavelengths below 5 microns. No limit is specified at longer wavelengths. The SiO coating of the scan mirror imprints a small amount of polarization on the inherently unpolarized thermal emission from the atmosphere. The interaction between the rotating scan mirror and the polarization dependent transmission of the spectrometer can be accounted for in the ground-based calibration, provided that the instrument polarization amount and angle and the scan mirror polarization (at 45 degree incidence angle) are measured at all wavelengths. The calibration error due to polarization not removable by the ground-based calibration is part of the system calibration error budget.

The AIRS radiometric calibration accuracy must be achievable and demonstrated at all scan angles. The main scan angle calibration dependence is introduced by the interaction between the scan mirror induced polarization of the unpolarized thermal radiance from the scene and the calibration blackbody and the spectrometer transmission function, which is a function of polarization.

The dynamic range of response (covering from 3K cold space to 352 K in equivalent blackbody temperatures) is another requirement that involves measurement and calibration, in terms of optimizing the offset and gain of the signal channels to permit accurate analog and digital processing as well as transmission to earth.

2. Sensitivity (NEN)

The sensitivity of AIRS measures the ability to detect small changes in radiance (noise-equivalent-radiance, NEN). Knowledge of the NEN is important for two reasons:
a) This sensitivity corresponds to specified noise-equivalent temperature differences (NEΔT) at a reference target temperature (250 K). It is part of the random radiometric error of every measurement, which has to be included in the derivation of the error estimate of the level 2 products.
b) It is part of the sensitivity specified contractually in the FRD. For most channels the specified NEΔT at the reference target temperature of 250 K is 0.2K.

3. Spectral Calibration

The IR spectral calibration consists of measuring, for each of the 2500 AIRS spectral channels, the   shape of the spectral response function (SRF), loosely characterized by the full width at half peak (FWHP) of the SRF, and the absolute wavelength position of the centroid of the SRF. Precise knowledge of the SRF centroid and low-level wing response are key to the ability of the AIRS to achieve high vertical resolution, The FRD specifies that the FWHM has to be measured with 1% accuracy, the centroid of each SRF has to be measured with an accuracy of 1% of the FWHP and the low-level response must be measured to 1/3000 of the peak response.

An important FRD requirement is that the centroids of the SRF do not shift as the instrument passes from the day-side to the night side of the orbit. The FRD specification allows ±0.05*FWHM of shift during 14 orbits (24 hr).

4. Spatial Response

Two relationships have to be calibrated:

a) The AIRS field of view, nominally 1.1 degree (FWHP) diameter and the wing response;
b) The relative superposition accuracy of the field of view of all wavelengths.

While the FOV does not directly enter in the AIRS retrieval algorithm, the simultaneous solution for atmospheric and surface parameters implies that all FOV at all wavelength are precisely coaligned. The FRD states the co-alignment requirement as 99%, and mathematically states this requirement in terms of the C_{ij} parameter, where (i) and (j) refer to the spatial response from the i-th and j-th spectral sample. Although all AIRS channels share the same field stop, diffraction and vignetting produce spatial differences in the field-of-view response function as a function of wavelength.

2.1.2. Vis/NIR Sensor

The Vis/NIR channels have no absolute radiometric calibration requirement from the FRD. Instead, a photometric precision requirement of 0.4% can be derived from the FRD, which calls for a minimum signal-to-noise ratio (100:1) when viewing a source of 0.4 albedo in sunlight. The dynamic range for the Vis/NIR channels (400:1) requires measurement and calibration as well. The spectral range, polarization (limited to 5% of the signal), spatial response   and boresight relative to the IR must be calibrated.

2.2. AIRS Test and Calibration Facility (ATCF)

Calibration and Characterization of the AIRS is done in the AIRS Test and Calibration Facility (ATCF). In order to provide accurate calibrations and to checkout and align the AIRS system, the Ground Support Station (GSS) in the ATCF is designed with the capability of simulating the expected spacecraft environment from the optical, radiometric, thermal, vacuum and low vibration viewpoints.
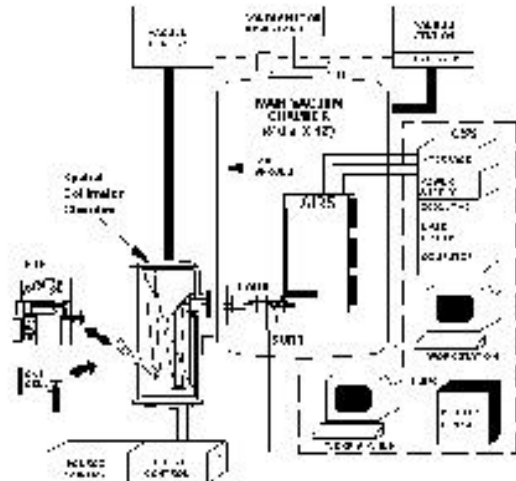
The ATCF design allows instrument access from a Class 10,000 clean room that will be devoted to final instrument checkout. The ATCF includes a large vacuum chamber, referred to in the following as the TVC, for final calibration and thermal vacuum testing. The chamber is located next to a service room, in which the pumping and power control systems are located. The final instrument assembly and checkout are supported by Class 100 and Class 1000 rooms connecting with the ATCF room.

Fig. 2.1. AIRS Test and Calibration Facility

2.2.1. ATCF Thermal Vacuum Chamber

The final calibrations and thermal vacuum tests will be carried out in the ATCF main vacuum chamber, the TVC. This chamber is an 8 foot diameter horizontal cylindrical vacuum vessel, 12 feet long, flanged and capped with domed access doors at both ends. Within this main chamber, the entire AIRS instrument is mounted within a fixture to allow its rotation ±90 degrees, so that the various calibrating sources can be viewed at any instrument scan mirror angle and the effects of gravity on instrument alignment and spectral resolution can be assessed. The radiometric calibration large area blackbody (LABB) and cold space view blackbody (SVBB) sources (section 2.2.2) are located within the TVC close to the instrument. A large port with a gate valve connects this chamber with a spatial collimator and other external calibration sources. This arrangement allows either instrument or calibration apparatus to be adjusted separately without affecting the vacuum in the other part.

In order to ensure accurate radiometric calibration of the instrument, it must be operated in an environment which closely simulates the operational space environment. Thus, the interior walls of the TVC will be cryogenically cooled to suppress thermal background. An earth background target will be placed adjacent to the nadir side of the instrument to simulate the upwelling radiation from the earth. Apertures within this target allow the instrument to view the various calibration sources, as required. Liquid nitrogen (77 K) will be used to cool the walls, parts of the instrument and calibration apparatus as needed, and heaters mounted on these walls and apparatus will enable rapid warm-up.

All vacuum chambers are evacuated from the service room behind the ATCF with high capacity roughing pumps, and then brought to operational vacuum ($<10^{-5}$ torr) with high capacity turbo-molecular or helium cryopumps. A mass spectrometer type of residual gas

analyzer will be used to monitor the T/V chamber for contaminants and trace gases (e.g., helium). Temperature-controlled Quartz Crystal Micro balances (TQCM) will monitor molecular contaminant depositions within the chamber, and witness plates will be used to collect particulate contaminants during times the chambers are at ambient pressure. Ion gauges will be used at several points to observe the vacuum pressures.

Figure 2.1 shows, schematically, the instrument and calibration apparatus in the ATCF, with the required controls and support facilities. The sources used for the radiometric calibration, a large area blackbody (LABB) and the space view blackbody (SVBB) reside with the instrument inside the TVC. For measurements of the instrument radiometric response, the AIRS scan mirror is rotated to view the LABB source and the SVBB, either as part of the routine scan every 2.667 seconds, or in a stare-mode.

A small blackbody can be directed through the FT-IR Spectrometer or a gas cell, or can be viewed directly by AIRS through beam expanding optics. Special cooling plates simulate the instrument to satellite thermal interface and cooling coils built into the instrument radiators allow rapid cool down of the instrument optics for its test and calibration. The cooling coils will be disconnected only for verification of the performance of the instrument radiative coolers.

2.2.2. Radiometric Calibration Sources

The final radiometric calibration is performed inside the TVC using a full aperture, large area blackbody, the LABB, and a simulated space view black body, the SVBB. Figure 2.2 shows a schematic view of the LABB and the SVBB. The LABB and the SVBB, procured from BOMEM in Quebec City, Canada, were designed to NIST standards. Both sources use the same wedge shaped cavity design with a 27.25 degree wedge angle. Incoming stray radiation undergoes more than six reflections prior to leaving the cavity. The cavity is coated internally with a glossy black paint (Aeroglaze Z-302). The measured BRDF is approximately 1E-4/sr. The LABB has an aperture of 4.68 x 2.08 inches located 11.5 inches from the scan mirror. It provides the full-aperture radiometric calibration reference source. The LABB can be set at any temperature between 197 K (using nitrogen gas for cooling) to 352K, the expected dynamic range of the AIRS spectrometer, using electric heaters. A sweep from 197K to 352K takes about 3 hours. Temperature knowledge and control are critical for accurate calibration.

The LABB uses 2 precision Platinum resistance thermometers (PRT) in the critical radiating surfaces and 3 additional PRTs in less critical areas. The five sensors typically agree to within 0.1K. The radiometric output of the LABB is NIST traceable through the calibration precision PRTs.

The SVBB is cooled with liquid nitrogen to a temperature of about 85K. Its aperture is 7.64 x 2.9 inches, at 7.4 inches from the scan mirror. This size is adequate to cover two contiguous space looks with the scan mirror rotating at the nominal scan speed. The SVBB temperature is monitored by two PRTs.

Figure 2.2 LABB and SVBB design overview.

Any SVBB temperature less than 100K produces a negligible signal in the AIRS spectral range. Below 85K the apparent signal from the SVBB is dominated by residual scattered light from the outside of the AIRS at 300K. The difference between the SVBB signal at 100K or lower and the signal expected from cold space (the 3K background radiation) is negligible. The folding design was required by physical envelope constraints in the TVC.

2.2.3. Spatial Collimator/Gas Cell

A spatial collimator, procured from BOMEM in Quebec City, Canada, is used to optically feed signals from external sources to the AIRS instrument in the TVC. Figure 2.3 shows a simplified schematic of the spatial collimator connected to the FT-IR.
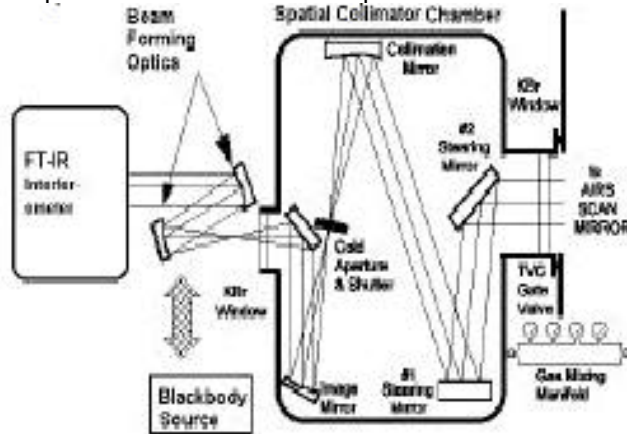
A source (or image of a source) located about 3" outside a KBr window is re-imaged at 1/3 scale by an 8" diameter f=20" spherical mirror in a focal plane. Located in the focal plane are a variable aperture, a four-position filter wheel, and a chopper, all cooled with cold liquid nitrogen gas to a temperature of 150K. An 8" diameter f=30" off-axis parabolic mirror re-images the source to infinity. Two flat mirrors can be articulated such that the direction of the collimated beam presented to the spectrometer pivots about the AIRS entrance aperture.

Figure 2.3. Simplified schematic of the spatial collimator connected to the FT-IR.

A source filling the maximum image diameter of 0.66" corresponds to a 1.26 degree diameter source at infinity. The cold chopper blade can be inserted into the beam periodically to provide a low signal reference in order to mitigate 1/f noise and drift in the AIRS electronics for tests where the AIRS scan mirror is locked into a fixed position.

The spatial collimator has three applications:
1. The far-field spatial response of AIRS can be mapped by moving the image of a source defined by the variable aperture in an x-y raster scan up to 4 degrees off the AIRS optical axis. The motion from a 0.05 degree step settles in 500msec. The spatial collimator is evacuated for this test.
2. For SRF shape and centroid calibration the spatial collimator is used to couple the FT-IR into the TVC, as shown in Figure 2.3. The spatial collimator is evacuated for this test.
3. For absolute spectral calibration a blackbody source is positioned at the first KBr window and the spatial collimator is filled with selected gases at low pressures. The effective path length is 6.4 meter. A second KBr window at the TVC gate valve is used to maintain the vacuum in the TVC. In this mode the chopper cannot be cooled.

2.2.4. Spectral Calibration using the FT-IR Spectrometer

A moderate resolution FT-IR spectrometer, a Bruker Instruments Model IFS-66V, is used for the spectral calibration of AIRS. The spectrally modulated 1.6 degree diameter beam from a small blackbody passes through the FT-IR and some transfer optics (including a one inch diameter integrating sphere), through a KBr window into the spatial collimator. From there the beam is directed through a gate valve into the vacuum chamber, where if fills the 1.1 degree field-of-view at the entrance aperture of AIRS. The FT-IR has a maximum spectral

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resolution of 0.1cm^{-1} using two-sided interferograms with 5 cm maximum optical retardation. The Bruker step control electronics is locked to the AIRS data system and uses a "step and integrate" approach. Each step and settle, occurring during one 22 msec dwell time of AIRS, is followed by N dwell periods of data taking. The parameter N is selected to achieve adequate signal-to-noise in the spectrum. Typically, 1<N<20. The interferometer mirror steps in multiple units of the HeNe laser wavelengths, 0.6329µm. The number of HeNe wavelengths per step is selected to prevent undesirable folding of the spectrum. Typically the steps are in the 3 to 20 HeNe wavelength range, depending on the wavelength range of the arrays under test. The interferograms are relatively short, 8194 points are typical to characterize all SRF of the AIRS with the required accuracy. The modulated signal produced by the Bruker is recorded as an interferogram by each AIRS detector. The inversion of the interferograms yields the SRF of all detectors.

The spectral resolution of the Bruker is a factor of at least 5 better than the spectral resolution of AIRS. The spectral response function of the Bruker will be verified directly by taking spectra of a gas cell filled with a known gas at a known (low) pressure and comparing the observed "line width" with the theoretically expected width of the spectral response function based on the maximum optical retardation of the FT-IR. The accuracy of the centroids of the SRF measured with the FT-IR are validated by comparing the observed spectral features in the transmission spectrum of a gas cell with the calculated values.

2.2.5. Other ATCF Associated Equipment

In addition to the contamination monitors mentioned above, a number of vacuum and temperature gauges are located at key points throughout the ATCF. An oxygen monitor and alarm are located in the Class 10,000 room housing the chamber to warn of low ambient oxygen levels at any time when nitrogen cooling or purging is in process.

2.3. Standards

The pre-flight radiometric calibration utilizes the large area blackbody source (LABB). The radiometric output of the LABB is indirectly traceable through characterization of its PRT's and analysis to the National Institute of Standards and Technology (NIST) as a secondary standard. The flight radiometric calibration source will be calibrated in the ATCF to the secondary standard. The flight calibrator radiometric output is indirectly traceable through the characterization of its resistance thermometers to NIST.

Numerous molecular line wavelengths are very accurately defined in the literature, often from NIST measurements. Infrared calibrations using molecular line references are easily available to any laboratory in the form of either gas emission or absorption. The ATCF uses the spatial collimator chamber as a low pressure controlled gas cell (section 2.2.3.) to provide molecular line references against a warm blackbody source.

2.3.1. Accuracy/Precision

The required accuracies for the radiometric, spectral, spatial and photometric calibrations of AIRS flow from the instrument level Functional Requirements Document (JPL D-8236). Detailed error budgets for the radiometric, spectral and photometric calibrations appear in Figures 5 - 8, of the AIRS Calibration Management Plan. The allocations to pre-flight ground calibration, in-flight calibration and instrument stability and other factors are evident in the figures. Preliminary radiometric accuracy estimates are shown in Appendix A for operation of AIRS after nominally five years in orbit. The projections are within the requirement for all wavelengths and scene intensities over the full scene dynamic range. The projections represent the most stressing condition of low scene radiances, and five year scan mirror contamination and aging of the electronics due to

the natural nuclear radiation environment. At higher scene brightness and at the start of the mission , the relative errors would be well below the requirement at all wavelengths.

It is anticipated that the required spatial relative angle measurement accuracies will be of the order of 0.020 for angles > 1degrees, and of the order of 0.002 for angles < 1 degrees, in order to properly characterize the instrument spatial response.

2.3.2. Traceability

The ATCF and flight calibration source components will be calibrated by NIST against primary physical standards, and the flight radiometric and spectral sources will be calibrated against the ATCF secondary standards. Complete documentation will be provided with the AIRS system to establish traceability. Spectral calibrations will be performed in the ATCF using a gas cell as discussed in section 2.2.4.

2.4. Pre-Flight Calibration

All AIRS system and subsystem parameters which are required to convert the sensor output to radiant input in physical units will be quantified during the pre-launch instrument calibration. The calibration results in the form of computer-readable tables as functions of digital number, voltage, temperature, etc., and/or coefficients of analytical fits will be provided with the deliverable hardware. Subsystem calibrations require direct measurement before assembly; e.g., thermistor calibrations, electrical gain/offset calibrations, emissivity, reflectivity, or transmissivity measurements of optical components, alignment of position shaft encoders, geometric layout of the focal plane detectors, radiometric focal plane maps and numerous other parameters.   System calibration is performed by measuring response parameters as functions of temperature, voltage, scan angle, alignment condition, etc.

2.4.1. Subsystem Calibrations

Various aspects of the AIRS system are determined and fixed at the subsystem level, and hence can and in many cases must be calibrated prior to the assembly of the entire system because of the physical difficulty of post-integration calibration.   Examples of this include the alignment of the scanner subassembly and the measurement of the relative alignment of the detector arrays. In some cases, calibration at this level impacts the critical, system level, parameter test strategies, and hence special attention is implied. The validation of each subassembly will require specific and generally unique bench fixtures and test apparatus.   All such subsystem data will be entered into the AIRS Data Analysis System, a part of the ATCF. Some data obtained will require manual input to this system, but data input will be automated to the maximum extent feasible.

Various tests of the AIRS spectrometer grating, mirrors, filters and the detector array will be performed at component or minor subsystem levels.
1. The reflectivity of the scan mirror at 45 degree incidence angle for the s- and p-polarization components will be supplied by the vendor as function of wavelength between 0.4 μm and 15.4μm. For error analysis we have assumed that p-reflectivities error is 2%, the s-reflectivity error is 0.5%.
2. The on-board spectral reference assembly, a mirror at approximately 300K, the predicted equilibrium temperature of the scan mirror assembly, is coated with a 12 micron thick layer of Parylene C (Figure 1.6). This refence source is used for mainly for ground-testing and wavelength stability tests. The transmission spectrum of a witness sample is obtained with the FT-IR.
3. The spectral calibration of the Vis/NIR Sensor Assembly will be determined analytically from component level data. A direct measurement of the spectral response of the Vis/NIR subsystem is not required.

4. The Vis/NIR photometric calibrator assembly will be characterized for its spectral brightness level, repeatability, stability and uniformity using a commercial filter photometer.

2.4.2. Pre-launch major subsystem and system calibration

The calibration of AIRS at the major subsystem level is accomplished in the mini-chamber. The calibration of the fully assembled and integrated AIRS system is accomplished by mounting it in the TVC and operating it from the GSS console. The TVC provides a simulation of the EOS satellite environment, and the GSS emulates the spacecraft electronic/data interfaces. The AIRS system is illuminated with various signals from the calibration apparatus under suitable environmental conditions, depending on specific functions being exercised.

2.4.2.1. Infrared Spectrometer Calibration.

The spatial, spectral and radiometric calibration requirements of the AIRS infrared spectrometer system can be accomplished and validated by ten distinct calibration procedures. These key calibration experiments are summarized in Table 2.1. Some of these experiments are repeated several times to evaluate the instrument response under a variety of conditions.

	PARAMETER	FRD VALUE		MEASUREMENT APPROACH	CALIBRATION AT LM	LEVEL 1B CALIBRATION
1	Radiometric Calibration Accuracy	3 or 50/SNR	%	Full-field blackbody measurement	Accuracy of calibration proven by analysis	Curve fit to minimize non-linearity
	Scene Dynamic Range	195 - 357	K	Full-field blackbody measurement	Acceptance test to demonstrated FRD compliance	
2	Instrumental Polarization	<0.25% at λ < 5μm		Rotate infrared polarizer between a black-body source	Establish FRD compliance	Measure polarization angle and amount (principal axis) at all wavelengths for use in the calibration equation
3	Scan Response Uniformity	<± 2	%	Full-field blackbody measurement.	Measure for all scan angles ±50 degrees	Use this test to validate polarization correction algorithm
4	Sensitivity (NEΔT)	3.74- 4.17μm 0.2 4.17- 4.21μm 0.14 4.21- 13.4μm 0.2 13.4- 15.4μm 0.35	K	Full-field blackbody measurement at 250K	Characterize rms noise at full dynamic range	
5	Spectral Coverage	3.74μm to 4.61 μm, 6.20 μm to 8.22 μm, 8.80 μm to 15.4 μm		FT-Interferometer	Demonstrated FRD compliance	
	SRF FWHM @ 14μm Width at 50% of area Width at 95% of area Area outside λ± 6Δλ	Δλ=λ/R R=1200 ± 5% @ 14μm, elsewhere 900< R < 1400 < Δλ < 2 Δλ < 1/3000 of peak		FT-Interferometer	Demonstrated FRD compliance	Tabular SRF at all wavelength with more than 1/3000 of peak response
6	Wavelength Calibration knowledge stability in 24 hours	0.01 0.05	Δλ Δλ	Gas cell at nadir view at one gas pressure, one source temp.	Demonstrate FRD compliance. Part of SRF calibration	Validate the spectral and radiometric calibration algorithm
7	Spatial Response IFOV FWHM 99% of power 99.95% of power	1.1 <2.5 <7.5	deg.	<0.3 degree diam. point source raster scanned in azimuth and elevation	Demonstrate FRD compliance. Test in nadir viewing position only	
8	Measurement Simultaneity	> 0.99		Calculated from spatial response test data.	Calculate Cij	
9	End-to-end Spectral calibration verification			View gas cell a t 2 or more pressures and source temp's	Conduct test only	Verify positions of lines (and line widths at 14 microns)
10	End-to-end calibration verification			View up through one standard air mass. Clear sky required.	Conduct test only	Compare with calculated spectrum based on known T(p), q(p). Compare with other spectrometer.

Table 2.1. Key Instrument Calibration Tests

1. Calibration Accuracy and Dynamic Range

This calibration procedure uses a large area black body (LABB) and a Space View Black body (SVBB). The SVBB serves as the cold space (zero radiance input). Dynamic range is measured by warming the LABB from 197K to 352K by applying heater power. During this entire time the AIRS instrument scans through its normal scan pattern, i.e. every 2.67 seconds the LABB is viewed at nadir, the SVBB is viewed in space view position and the flight calibration blackbody is viewed in the anti-nadir position. This process takes about three hours. The change in LABB output during this experiment fully characterizes any non-linear aspects of the AIRS system transfer function. The procedure is then repeated by cooling the LABB to197K, again in about 3 hours. A comparison between the transfer function derived from the LABB warming and the LABB cooling experiments provides an estimate of the error due to possible hysteresis effects in the LABB instrumentation.

This procedure, done simultaneously for all 2500 AIRS spectral channels, establishes the end-to-end radiometric transfer curve (needed for the linearity correction), and the dynamic range.

2. Instrument Polarization.

The AIRS spectrometer transmission is polarization dependent. The instrument polarization measurement uses the spatial collimator with an external blackbody source. Three of the four positions of the cold filter wheel in the spatial collimator are occupied by Wire-Grid Polarizers, oriented at 0, 45 and 90 degrees relative to the instrument +z axis (nadir view). Measurements at three angles suffice to determine the polarization amount and the angle, using a data reduction algorithm documented in Lockheed Martin Memorandum dated 28-April 1997 by George Gigiolo. The Wire-Grid Polarizers are made by Perkin-Elmer on a silver-bromide substrate. For a spectrometer polarization of 0.33 the accuracy of the polarization measurement is estimated to be ± 0.02, with an uncertainty of the polarization major axis of ± 1 degree. These uncertainties are included in the radiometric calibration error estimate. The polarization induced by the scan mirror on the unpolarized radiance emitted by the LABB (or the upwelling spectral radiance from the Earth) causes a scan angle dependent modulation of the observed signal. The scan mirror is locked to the exit port position for this experiment.

3. Scan Response Uniformity.

Experiment number 1 demonstrates the calibration accuracy over the full range of temperatures, but only for the nadir view. The AIRS radiometric calibration accuracy must be achievable and demonstrated at all scan angles. There are two possible sources of scan angle dependent response: Scan mirror polarization and scan mirror emissivity non-uniformity.

In section 1.5. we discussed the potential effect of projecting the AIRS apertures on the scan mirror. Details of this effect are analyzed in the AIRS Level 1b ATBD. The effect basically is due to the non-uniform emissivity of the scan mirror due to scan mirror contamination non-uniformity. Assuming that the spacecraft environment in orbit is equivalent to class 450, a 200 Angstrom thick film of molecular contaminants is expected to slowly build up during a five year mission. The non-uniformity of this film depends on the geometry of the exposed area. Since the AIRS scan mirror is well protected inside the rotating barrel baffle, a 20A rms film thickness variation is a worst case estimate. Based on industry sources a 100A thick film causes a 0.01 change in emissivity. The scan mirror emissivity after 5 years would thus have an 0.001 rms emissivity variation. This translates into an 0.15% rms variation in the signal from a fixed temperature source as a function of

scan angle. This error has been included in the radiometric calibration error estimate. The error is negligible compared to noise in the measurement.

The dominant cause of scan angle calibration dependence is introduced by the interaction between the scan mirror induced polarization of the unpolarized radiance from the scene and the spectrometer angle dependent polarization, measured in experiment number 2. The scan mirror polarization will be measured by the vendor at the subsystem level (section 2.4.1.) In this experiment the AIRS instrument and the SVBB are rotated from -50 degree to +50 degree, while the LABB remains in its original position. Two LABB temperatures will be used: 250K and 300K. Figure 2.4. shows the magnitude of the expected signal modulation due to the interaction between the scan mirror polarization and the spectrometer polarization at 9 micron.
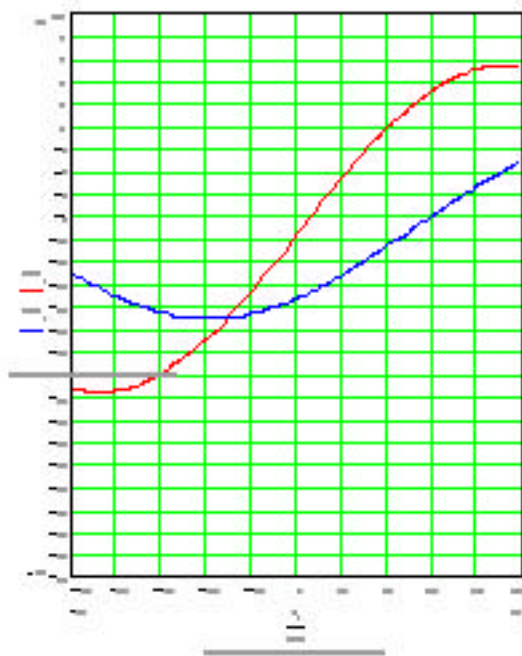
The solid line (starting at -23 dN) is calculated for a 250K, the dotted line (starting at -13 dN) for 300K target, assuming 33% spectrometer polarization with a 25 degree angle between the major axis and nadir. The scan mirror reflectivity of the p- and s-components is 0.98 and 0.80, respectively. The scan mirror temperature is assumed to be 264K, and the calibration blackbody is at 310K. The correction term varies from -13*NEN to +5*NEN for a 300K signal. The 300K signal is equivalent to 570*NEN. After the correction using the level 1b calibration software (Table 3), this effect is reduced to a fraction of one NEN, provided that the spectrometer polarization and the scan mirror polarization were determined with the accuracy given in section 2.4.2.1. paragraph 2.

Figure 2.4. Signal modulation due to scan mirror polarization

4. NEN System Sensitivity

For this measurement the LABB is stabilized at three representative temperatures: 197K, 250K, 310K. Once the LABB is stabilized at the desired temperature, e.g. 250K, the instrument executes its normal scan pattern for about 500 cycles (about 20 minutes). With the assumption that the detector responsivity does not change during 20 minutes, we use the statistics of (250K LABB - space) views and (300K flight blackbody - space) views. If X and DX are the mean and standard deviation of the 500 (250K LABB - space) views, and Y and DY are the mean and standard deviation of the 500 (300K flight blackbody - space) views, both in DN units, then

$NEN_{250} = 0.71* DX * B(n,300)/X$,

where B(n,300) is the blackbody radiance emitted by the flight blackbody at 300K at frequency n. We also measure

$NEN_{300} = 0.71* DY * B(n,300)/Y$

and verify that to good approximation $NEN_{300}=NEN_{250}$. In flight we measure NEN_{300} with adequate accuracy with a sequence of about 100 scan cycles.

In addition to the analysis of (LABB-SVBB) differences measured within a fraction of a second of each other, the 20 minute time series of SVBB and LABB views will be also be analyzed for 1/f noise or unexpected periodicities.

Using the LABB at 310K transfers the NIST traceable calibration of the LABB to the AIRS flight calibration blackbody.

5. Spectral Coverage and Resolution.

The IR spectral calibration is the most critical element of the AIRS pre-launch calibration. It consists of measuring, for each of the 2500 AIRS spectral channels, the spectral response function (slit response functions, SRF), loosely characterized as the full width at half maximum (FWHM) of the SRF, and the position of the centroid of the SRF, i.e. the absolute wavelength knowledge. Precise knowledge of the SRF FWHM and centroid is key to the ability of AIRS to achieve high vertical resolution. In orbit the centroid position and the FWHM of the SRF have to be known with 1% of the FWHM accuracy. The spectral SNR required to achieve a given measurement accuracy for the centroid and FWHM is given in Table 2.2. The actual prelaunch measurements have to be to somewhat higher accuracy due to the presence of other sources of uncertainty. Details of the SRF centroid and FWHM end-to-end error budgets are present in Tables 2.3. and 2.4. for three representative wavelengths.

Prelaunch SRF Calibration Errors (FWHM units)		
SNR SRF	**Centroid Error** SNR & Software	**FWHM Error** SNR and Software
100	0.0100	0.2459
200	0.0050	0.0103
300	0.0033	0.0072
500	0.0020	0.0048
1000	0.0010	0.0033
2000	0.0006	0.0028
3000	0.0004	0.0027
10000	0.0003	0.0026
30000	0.0003	0.0026
Software	0.0003	0.0013

Table 2.2. Prelaunch SRF Calibration Uncertainty as Function of SNR

The spectral measurements are accomplished simultaneously for all detectors by inserting a Fourier Transform Spectrometer (FTS) between an external blackbody source and the entrance aperture of the spectrometer. As the FTS mirror is scanned from its maximum optical retardation to zero path differences, an interferogram is measured by each AIRS detector. The Fourier transform of each interferogram produces the shape and the centroid of the SRF for each detector.

	SRF Centroid Errors Budget for three wavelengths		
	4.2 μm	9.8 μm	15.4 μm
RSS SRF Centroid Error (FWHM units)	**0.01**	**0.01**	**0.01**
Prelaunch Ground Calibration	**0.00469**	**0.00469**	**0.006557**
SNR	0.002	0.002	0.005
Illumination Non-uniformity	0.002	0.002	0.002
FTS Obliquity	0.001	0.001	0.001
Launch Induced Non-recoverable	0.003	0.003	0.003
SRF Centroid Estimation Software	0.002	0.002	0.002
In-orbit Stability (between Cal's)	**0.004899**	**0.004899**	**0.004899**
Thermally induced Shifts	0.004	0.004	0.004
Internal Vibrations	0.002	0.002	0.002
External Vibrations	0.002	0.002	0.002
Ground Software (level 1b)	**0.007348**	**0.007348**	**0.005831**
Signal averaged SNR	0.002	0.002	0.004
Focal Plane Model	0.005	0.005	0.003
Atmospheric Feature Knowledge	0.005	0.005	0.003

Table 2.3. End-to-End SRF Centroid Error Budget

	SRF FWHM Errors Budget for three wavelengths		
	4.2 μm	9.8 μm	15.4 μm
RSS SRF FWHM Error (FWHM units)	**0.0099**	**0.0099**	**0.0099**
Prelaunch Calibration	**0.009434**	**0.009434**	**0.009434**
SNR	0.007	0.007	0.007
FTS OPD & self apodization	0.006	0.006	0.006
FWHM Estimation Software	0.002	0.002	0.002
In-orbit	**0.003606**	**0.003606**	**0.003606**
Short term (vibration)	0.002	0.002	0.002
Long term (defocus)	0.003	0.003	0.003

Table 2.4 End-to-End SRF FWHM Error Budget

The error budget allocation differs by wavelengths. At 4.2µm there are no well resolved lines in the spectrum to aid the in-orbit calibration. The level 1b software for the centroid calibration thus depends on the accuracy of the focal plane model. From Table 2.3. it can be seen that the centroid calibration allocates the dominant error budget to the focal plane model and to the knowledge of atmospheric features. At 15.4µm spectral lines are well resolved, so there is much less dependence on the focal plane model for centroid calibration. At this wavelength SNR and OPD related issues (knowledge of the spectral response function of the Fourier Spectrometer) dominate the error budget allocation for measuring the FWHM (Table 2.4.). Validation of the budgetary error allocations is part of the EM data analysis tasks.

The 1.5 inch diameter exit beam from the Bruker is not uniform, but includes a central obstruction from the visible laser pick-off mirror. The entrance apertures of AIRS have to be uniformly illuminated. This uniformity can be accomplished by passing the beam through a 1 inch diameter integrating sphere (not shown in Figure 2.3). The effective insertion loss of the integrating sphere is about 0.0024. This large loss in signal can be recovered at all but the longest wavelengths by increasing the temperature of the external blackbody to up to its 1700C maximum. At the longest wavelengths the loss of signal can only be recovered by increasing the integration time.

Table 2.2. shows that the spectral calibration accuracy is directly related to the SNR. The SNR can be improved by increasing the time allocated to a measurement. The time allocation in the ATCF has been based on the error allocation budget. We use the 15.4µm region as an example. From Table 2.4. the allocation for FWHM to SNR is 0.007. From Table 2.2. we see that 0.007 accuracy requires spectral SNR=300. This spectral SNR can be achieved with an interferogram SNR=30 at zero-path-difference with a interferogram run time of about 2 hours. The calibration is carried out simultaneously for all wavelengths. At shorter wavelengths the availability of SNR in the interferograms is not an issue. At 4.2µm interferograms with adequate SNR could be achieved with 15 minute run times.

The FTS is used to measure the detailed SRF shape and the SRF centroid, λ_i, of each of the 2500 spectral channels in each of the 12 arrays in the AIRS focal plane. The SRF centroid location is a function of the spectrometer design, chiefly the grating constant, the incidence angle on the grating, the focal length and tilt angle of the collimation mirror, and the distance of the focal plane from the collimation mirror. Several of these dependences are due to temperature or temperature gradients within the spectrometer. The tilt angle and the focal plane distance are adjustable in flight using the Adjustable Mirror Assembly (AMA).

As part of the detailed characterization of the spectrometer the SRF centroids could be measured, time permitting, in the ATCF for a number of conditions which represent a wider range of in-flight conditions, such as may be encountered by temperature abnormalities due to cold space view experiments. The resulting data set will be used to develop a better computer model of the spectrometer. The detailed characterization effort is not funded at present.

> 6. Spectral Calibration stability.

An important FRD requirement is that the centroids of the SRF do not shift as the instrument passes from the day-side to the night-side of the orbit. The FRD specification allows 0.05*FWHM of shift during 14 orbits (24 hr). This requirement is verified by operating the instrument for 24 hours in the test chamber, while heaters simulate the changing orbital thermal environment. Throughout this time the instrument executes its normal scan cycle. At the nadir position the instrument views an external blackbody through a gas cell (section 2.2.3) filled with a small amount of CO_2 at low pressure. The centers of CO_2 lines, resolved between 13 and 15 microns, are used to locate the centroid of a

spectral feature (covering perhaps 40 detectors) to within 0.01*FWHP with about 100 observations using the cross-correlation function between the observed spectrum and the calculated transmission spectrum of the gas cell.

7.   Boresight and Spatial Response

The scanned IR field of view is actually the superposition of several two-dimensional , 1.1 degree diameter angular field functions, that are positioned and aligned by the apertures, fieldstops and transfer mirrors of the system optical train. Diffraction produces spatial differences in the field pattern as a function of wavelength. In this experiment we determine full width at half peak of the AIRS beam (nominally 1.1 degrees) and the wing spatial response with a scan from -2 degree to +2 degree along two orthogonal axis centered on the geometric boresight. The x-y raster scan uses the spatial collimator stearable beam with an aperture of 1/4 degrees diameter and 1/8 degree steps. The AIRS scan mirror is locked for this test.

Boresight calibration of AIRS relative to reference optical surfaces (ROS's) installed on the exterior of the instrument will initially be established using laboratory ambient techniques. Entirely reflective optics in the scan mirror and imaging telescope allows direct observation in the visible of the telescope field stop for the IR spectrometer as well as the focal plane detectors for the Vis/NIR subsystem using theodolites or other standard alignment instruments. The IR boresight alignment will be obtained when the IR IFOV is mapped. The IR boresight is defined as the average over all spectral samples of the centroid positions of the two dimensional IFOV response functions. A secondary ROS mirror is installed temporarily near the scan mirror in the field of view of the ATCF collimator optics. Its alignment relative to the primary ROS on the instrument package is measured. Observation by retro-reflection of this ROS through the collimator optics during the IR IFOV mapping will allow relating the centroid of the IFOV to the direction of the normal to the secondary ROS.

8. Boresight and Spatial simultaneity.

In this experiment we raster scan   a 2 x 2 degree area centered on the geometrical boresight of the spectrometer with an 1/8 degree diameter beam and 1/16 degree steps, using the same basic technique as described in the spatial response test. The response at each x,y location, normalized to the unit area, from the   i-th detector is $r_i(x,y)$. The boresight of each detector is given by the centroid of the beam pattern. The centroid is measured by fitting a cylindrical top hat function or simple bell shaped curve to $r_i(x,y)$. The average of all centroids is the effective boresight of the spectrometer.

 The measurement simultaneity is calculated from the definition

$$C_{ij} = 1 - 0.5 * \int \int abs\,(\,r_i(x,y) - r_j(x,y)\,)\;dx\;dy$$

The contribution to Cij by the scan mirror will be the result of lack of flatness of the mirror and diffraction around its edges. The spatial collimator optics includes a gimbal mounted fold mirror which controls the direction of the collimated beam presented to the spectrometer assembly. Since there is no scan mirror to periodically view the space view blackbody source, the beam will be chopped every 2.667 seconds by the cold spatial collimator chopper in order to mitigate 1/f noise and drift in the AIRS electronics. With the subsystem so aligned, the collimator mirror is stepped through a raster scan while the response of selected detectors as a function of angular orientation is recorded.

In this test the scan mirror is locked into a fixed position to direct the AIRS beam through the TVC exit port.

9. Spectral end-to-end response verification.

This test is used to validate the absolute accuracy of the centroid positions of the spectrometer and to validate the spectral and radiometric calibration algorithm. For this test the AIRS is operated using the nominal scan sequence. In the nadir position the spectrometer views a 320K external blackbody through the transmission spectrum of CO_2 and N_2O at a number of low pressures. The resulting spectra are compared with calculated spectra. Analysis of these tests are AIRS science team member responsibilities.

10. End-to-end performance verification

This is the only test used to indirectly validate the performance of the AIRS spectrometer as a sounder, although only as an up-looking sounder. For this test the spectrometer is operated in the nominal scan mode. In the nadir position the spectrometer field of view beam is directed by a mirror (through about 30 ft of laboratory air) to the outside of the test facility. There the beam encounters another mirror, which directs it either down into a large calibration blackbody, or up through a vertical column of airs. The resulting spectra are compared with calculated spectra based on the known temperature and moisture profile. A comparison may also be made relative to a portable spectrometer, AERI, developed by one of the AIRS team members for use at an ARM site. Analysis of these tests are AIRS science team member responsibilities.

2.4.2.2. Vis/NIR System Calibration

The photometric precision, signal-to-noise ratio, dynamic range and spectral range and spectral response of the Vis/NIR channels will be established at the subsystem level by analysis of component level (optics, filters, detectors) characteristics measured by the respective component vendors. The spatial response of the Vis/NIR Sensor Assembly will be characterized at the assembly level prior to its integration into the instrument. The widths and centers of the linearly arrayed IFOV's will be measured in each of the four spectral bands and referenced to the assembly mounting interfaces.

The only planned system level test of the Vis/NIR channels is a measurements of the IFOV centers of each detector relative to the AIRS alignment reference cube. Each detector has a nominal field of view of 0.16 degrees. In this experiment the scan mirror is locked in the fixed position, as described in the spatial calibration of the IR system. The spatial collimator will use a small incandescent source (about 0.05 degree in angular extent) to map the field of view of the visible sensor elements. As of the writing of this calibration plan (October 1997) further details are not available.

The Vis/NIR channels are required to achieve 0.4% relative photometric accuracy at an albedo of unity. There is no absolute radiometric accuracy requirement for the visible channels. Since the absolute level of signal from the incandescent filament can be estimated to within about 20%, the planned system level test also establishes an adequate estimate of system level sensitivity and absolute calibration at the 20% level.

2.5. In-orbit Calibration and Calibration Monitoring

On-board calibration is provided for instrument IR radiometric calibration, knowledge of the center frequencies of each AIRS spectral sample, and Vis/NIR response stability. These three critical functions are likely to show a slow drift in time which, if not corrected periodically, would cause AIRS to fail to meet the measurement accuracy specifications. The AIRS radiometric and spectral calibrators are pre-flight characterized relative to NIST or well-established physical standards.

2.5.1. Inflight IR Radiometric Calibration

The in-flight infrared radiometric calibration utilizes two sources: One source is the flight calibration blackbody at a temperature of approximately 300 K, the nominal equilibrium temperature of the scanner subsystem. The other source is a view into cold sky. There are actually four separate views of cold space, two at the start of each scan line, and two at the end of each scan line. Based on observing the difference between the four cold views throughout an orbit, a decision will be made during the in-orbit checkout phase which of the four cold views, or what linear combination, to use for the offset correction. In combination the two sources are used to correct for changes in the electronic offset and the gain of the system. Both targets are full aperture calibrations, and include the scan mirror in the optical path. The calibration measurements are routinely performed on every scan (2.67 seconds). The actual calibration, i.e. the determination of the gains and offsets for each spectral channel, are carried out on the ground. The offset and gain coefficients for each detector are calculated, smoothed and applied during the level 1a to level 1b conversion during ground processing. Table 3.1. shows an algorithmic representation of the radiometric calibration used by the ground calibration software. Details are presented in the referenced AIRS Level 1b ATBD.

The time history of the gain of each channel and the difference between two adjacent space views is used by the ground data software to evaluate the quality of the calibration and the health of the system.

2.5.2. In-flight Spectral Calibration

The inflight spectral calibration relies entirely on the use of upwelling spectral radiance from the scene for the determination of the centroids of the SRF of each channel. This is made possible because the AIRS spectral resolution is adequate to resolve atmospheric lines. The calibration procedure is entirely analogous to the way the calibration algorithm is validated using the 24 hour test and the two procedures which validate the end-to-end spectral calibration in the ATCF. By using only spectra near nadir, the number of precalculated upwelling radiance spectra which need to be accessed by the ground-based spectral calibration algorithm can be limited to about ten. The spectral calibration uses the focal plane model developed during the pre-launch testing in the ATCF. An example of the upwelling spectral radiance and an "observed" spectral radiance is shown in Figure 2.5 for array M11.
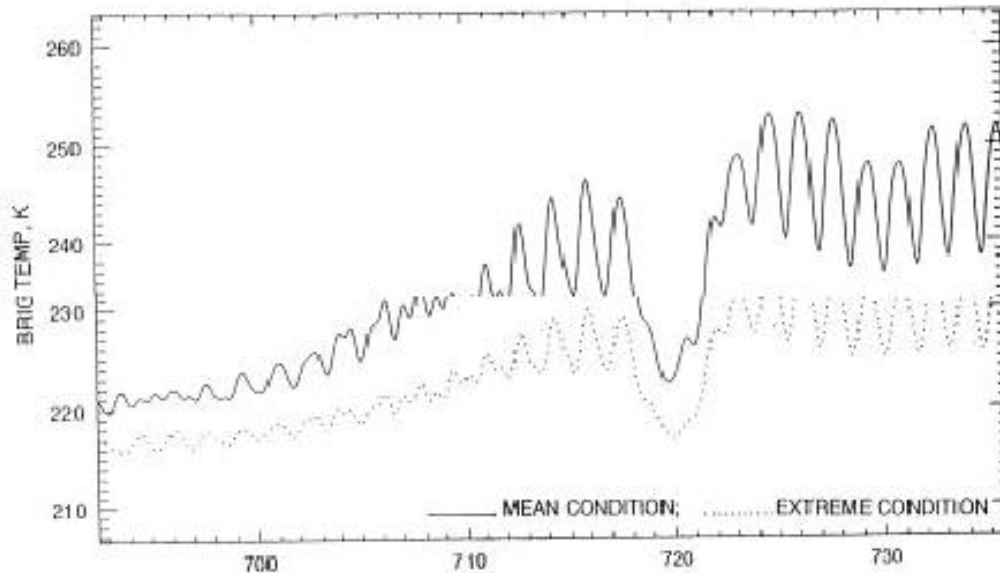
Figure 2.5. The spectrally resolved CO_2 lines in the 723 to 736 cm^{-1} region of the spectrum present an excellent region for spectral calibration.

The solid line in Figure 2.5 shows the calculated upwelling radiance spectrum in the 692-736 cm^{-1} region for a nadir view under (climatology) average mid-latitude, winter, night-time, and cloud-free conditions. The dotted spectrum shows what may be measured by the 144 detectors in array M11 for mid-latitude, winter, night-time with a 20K colder troposphere than expected from climatology.

For array M11 the spectral calibration algorithm searches for the peak of the cross-correlation function between the precalculated and the observed spectrum between 723 and 736 cm^{-1}. This spectral feature covers 42 spectral samples. The centroid of this spectral region can be located with an accuracy of $0.02*\Delta\lambda$ from a single observation at nominal SNR and spectral contrast. In practice, hundreds of upwelling spectra are available to maintain the inflight knowledge of the spectral calibration at the required $0.01*\Delta\lambda$.

2.5.3. Vis/NIR Response

The relative gain and offset of the Vis/NIR channels will be monitored once per orbit using the photometric reference lamps. The offsets are obtained with each view of the IR radiometric calibrator assembly, which will be dark in the visible and NIR regions of the spectrum.

The time history of the gain of each channel and the relative signal output from the primary calibration and the backup lamps is used by the ground data software to evaluate the quality of the calibration, the degradation of lamp output with age and the health of the system. Periodic vicarious calibration (i.e. observing well characterized ground sites, such as White Sands) and cross-calibration with MODIS will also be used to monitor the Vis/NIR response.

2.5.4. System Performance Monitoring

In addition to directly monitoring calibration related parameters, such as the stability of the gain of each channel, the system performance and its stability will be monitored in orbit by

observing the time history of all temperatures, currents and voltages which are identified as relevant during the AIRS flight model testing.

2.5.4. In-flight calibration Inaccessible Parameters

Certain parameters of AIRS, which are implicit in the conversion of data numbers to physical radiances, are not subject to calibration on orbit, since an on-board calibrator to measure the parameter is not included. These parameters will be carefully calibrated on the ground and the design of the instrument will be such to insure their stability or repeatability throughout the life of the mission. Design studies and test data, wherever possible, will be furnished to support the assumption of stability of these parameters. These flight-inaccessible parameters
include:

     (1) spectral response function (SRF - relative amplitude response calibration, including wing response and out-of-band rejection) for each spectral channel. The central portion of the SRF is dependent on the IR Sensor Assembly focus. The SRF will be calibrated for several focus conditions (see 2, below). The SRF centroid will be determined in-flight using the upwelling spectral radiance.

     (2) IR Sensor Assembly alignment, which is adjustable using the Adjustable Mirror Assembly (AMA) to compensate for potential alignment shifts and drifts in flight. The focus and lateral displacement conditions as functions of commanded AMA positions will be calibrated. Note the comments regarding a decision to use the AMA in the section on the spectral calibration algorithm, 3.2.3.

     (3) electronic transfer function of all Analog to Digital converters. The special diagnostic mode used in orbit to assess detector and electronics non-linearities involves staring at the radiometric calibrator and space while recording data with varying detector integration times. The integration times can be closely controlled. Since the amount of detector signal integrated in response to instrument background and calibrator photon flux is proportional to the integration time, the recorded digital response when compared to the integration time provides an estimate of the non-linear transfer function for each spectral sample in the instrument. However, because the integration times can be set only in fixed steps, this method only determines the transfer function in from 3 to 20 points covering the dynamic range, depending on the wavelength region.

     (4) cross-talk rejection of all focal plane multiplexers;

     (5) calibrations of all temperature sensors;

     (6) spectral emissivity of the radiometric calibration blackbody;

     (7) relative brightnesses of the triple redundant photometric calibrator lamps;

     (8) relative timing of the integration periods among all focal plane arrays to factor into Cij determinations since a temporal non-simultaneity multiplied by the normal scan rate results in a spatial non-simultaneity;

     (9) instrument polarization for two orthogonal polarization axes for both the IR and Vis/NIR Sensor Assemblies after integration with the Scan Assembly.

2.6. Documentation

All test data will be archived at the TLSCF. The data will be analyzed and reduced to readable formats, such as charts and graphs, as appropriate. These data will be presented as part of the final test procedure results. The raw test data, results of the data analysis and results of the instrument performance validation analysis will also be archived at the TLSCF.

3. Analytic Tools

3.1. Instrument Computer Model

3.1.1. Hardware contractor supplied models

The hardware contractor is responsible for the design and validation of a mathematical model of the instrument. This model is used to analyze the radiometric and spectral sensitivity of the instrument to noise, electrical or thermal disturbances.

A temporal model of the instrument has been developed, allowing computation of the system electrical response to integrated spectral sources, using simplified detector, grating, filter, and scanner functions. Additional models have been developed, including a radiometric transfer model, calibration error allocation analysis, detector models (Lockheed Martin proprietary), SRF (spectral response function model), interference filter model, a mechanical finite element model, and an on orbit spectral calibration processing performance model.

1. The radiometric transfer model examines thermal variability, drift, diffraction, scattering and stray radiation to determine instrument radiometric response.
2. The calibration error allocation analysis balances multiplicative, additive and non-linear radiometric and electronic errors to attain the desired accuracy.

3. The detector models predict the response of both the photovoltaic and photoconductive detectors with input irradiance, and include radiometric temporal and spectral response, dark currents, detector and photon noise, and non-linear effects.

4. The SRF function model provides an accurate simulation of the grating performance, including the effects of order overlap, optical aberration, focus/collimation effects, scattering and detector current diffusion.

5. The filter model replaces the simplified "square" filters in the overall instrument models with more realistic filter functions.

6. The mechanical model allows simulation of the thermal and mechanical dynamic distortions in the instrument to assess its spectral and spatial stability.

These models are engineering models developed on a variety of platforms and software packages. The radiometric transfer model with noise exists as an EXCEL spreadsheet as does the filter model. The slit response model has been developed on a VAX with FORTRAN and ASAP (Breault Research Organization, Inc.) elements. The mechanical and thermal models utilize commercial packages such as NASTRAN and SINDA running on Sun workstations. These models are developed and maintained by the Lockheed Martin engineering staff dealing with each respective technical area. The models can be transferred to the TLSCF at JPL as needed to support their efforts.

3.1.2. AIRS science team member supplied models.

The spectrometer model, the only model supplied by the science team, combines the data SRF centroids measured by the FTS in the ATCF into a single computer model. The combination of the spectrometer model with the in-flight spectral calibration data is used to assign a SRF centroid value to each spectral channel of AIRS.

The FTS is used to measure the detailed SRF shape and the SRF centroid, λ_i, of each of the 2500 spectral channels in each of the 12 arrays in the AIRS focal plane. The SRF

centroid location is a function of the spectrometer design, chiefly the grating constant, the incidence angle on the grating, the focal length and tilt angle of the collimator mirror, and the distance of the focal plane from the collimator mirror. Several of these dependencies are a function of temperature or temperature gradients within the spectrometer.   The tilt angle of the collimator mirror and its distance from the focal plane are adjustable in flight using the Adjustable Mirror Assembly (AMA). The SRF centroids will be measured in the ATCF for a number of conditions which represent the range of the expected in-flight conditions. The resulting data set will be used to develop a computer model of the spectrometer.

At the core of the AIRS spectrometer model is the grating equation

$$m* \lambda = d * (\sin \alpha + \sin \eta),$$

where m is the grating order, λ is the wavelength, d is the grating constant (the spacing between the rulings of the grating), α is the angle of incidence of the collimated light on the grating, and η is the angle of the diffracted light leaving the grating. In the case of AIRS m ranges from 3 at the longest wavelengths to 11 at the shortest wavelengths. We can express the wavelength λ_i of the i-th detector of array j as

$$\lambda_i = d/m * (\sin \alpha + \sin(\text{atan}((Xo + Xj + (i-1)*p_i)/L)))$$

where L is the distance of the focal plane from the apex of the collimator mirror, p_i is the detector pitch in the dispersion direction and Xj is the origin of the j-th array relative to the focal plane origin Xo.

For each spectral calibration run (requiring about 4 hours of test time) for one condition of the spectrometer, i.e. a given setting of the AMA , grating temperature and focal plane temperature, we obtain 2500 values of λ_I . This represents 2500 equations to solve for 27 parameters: d, L, α, 12 Xj, 12 p_i, in a least squares sense. The first guess for L, α, Xo, Xj and p_i are their geometric values. The diffraction order m is always the integer given by the order selection filter for the array. The key algorithm of the program is a simplex search for the minimum of $\Sigma (\lambda_i - \lambda o_i)^2$, where λ_i are the measured wavelengths and λo_i are the wavelengths calculated from the model equation.

Information about the in-orbit spectral calibration of AIRS is obtained on every scan line (every 2.67 seconds) from the view of the spectral radiance from the target near nadir. We expect to obtain the mean position of six of the 12 arrays based on spectral features similar to the one shown in Figure 2.5. Based on the thermal characteristics of the focal plane material we assume that the detector pitch p and the relative position of the 12 arrays is given by the values determined in the ATCF. We assume that the grating constant d can be calculated from the grating constant d_o, measured empirically in the ATCF at grating temperature T_o, by adjusting it for the known thermal expansion coefficient of Aluminum. We thus have six equations to solve for 3 spectrometer model parameters: L, α, and Xo, using a least square residual metric.

The validity of the spectrometer numerical model and the validity of the assumption required to use this model for the in-orbit spectral calibration will be first tested using the engineering model. The data will be used to evaluate if the linear focal plane model is sufficiently accurate. With a quadratic focal plane model $(i-1)*p_j$ is replaced by $(i-1)*(p_j+(i-1)*q_j)$. This would increase the number of parameters in the spectrometer model to 40. Final adjustment of the model requires testing of the flight model using a representative set of spectrometer temperature and adjustment conditions.

3.1.3. Vis/NIR Instrument Models

There are two computer models for the Vis/NIR detectors. The first is a spectral and spatial response model, discussed in section 2.4.1. This model, supplied by the instrument

contractor, uses the manufacturer supplied component specifications to calculate the instrument's spatial, spectral, and polarization response. In addition, the AIRS science team has developed a parameterized instrument model for Vis/NIR imaging, geolocation, and spatial calibration tasks. This model is described in the previously referenced AIRS Vis/NIR Geolocation Algorithm document (JPL-ADF-265). The model converts line and sample numbers of detector pixels into instrument, spacecraft, inertial and geocentric coordinate systems.

3.2 Calibration Algorithms

The engineering model tests are the first opportunity to evaluate the spectral calibration algorithms using real experimental data sets. The final development and refinement of the algorithms and, of course, parameter tables, must utilize the test data results obtained with the flight instrument.

3.2.1. Radiometric Calibration Algorithm

Every sensor output that will be transmitted to the ground stations will require transformation to extract the true measurement or indication. The result of all transformations is the level 0 to level 1 conversion from digital counts to physical units. Information about the radiometric calibration of AIRS is obtained on every scan line (every 2.67 seconds) from the view of the black-body calibration target and the cold space views. However, in order to minimize the effects of observational noise, the calibration data will be passed through a triangular smoothing window, centered on the observation to be calibrated. This extends from (at most) 50 scan lines before to (at most) 50 scan lines following the observation. This procedure eliminates the effect of linear drift between calibration observations. Because the engineering model does not include the scan mirror assembly, including the scan mirror and calibration blackbody, it can not be used in the large ATCF test chamber, which includes the LABB and the SVBB. Evaluation of the maximum usable smoothing window has to be deferred to the flight model testing in the ATCF.

Corrections are applied in the reverse sequence to the order errors are introduced in the instrument signal chain. The digital multiplier gains that are used in each detector channel prior to transmission can vary by ground command, and the values of gain used, constituting a part of the data stream, will be applied. Corrections determined in ground calibration or special flight diagnostic modes are then made for non-linearities from the detectors themselves and from the signal channel electronics. The next correction is the offset adjustments for all spectral samples in accordance with space views. Following this, gain adjustments for all spectral samples in accordance with on-board calibrator views are applied. Finally the calibration is corrected for the scan angle dependent polarization effect. Table 3.1. shows an algorithmic representation of the radiometric calibration. Validation of the polarization correction term is the major objective of measurement of the scan angle dependence of the signal in the ATCF.

1	K= Table(DN)	Convert from raw data numbers (12 to 16 bit integers) to engineering units K, 32 bit floating point numbers.
2	V= f(K)	Convert from K to V, by applying the non-linearity correction
3	$G = NC1 / (Vc - Vs)$ $N1 = G * (Vt - Vs)$	Apply two point calibration where N1 is the observed radiance to first order, Vt is the observed signal from the target at scan angle δ, Vs is the smoothed zero-flux equivalent voltage corresponding to scan angle δ. Vc is the smoothed reading observed when the scan mirror is in the black-body view position. The smoothing suppresses the drift and noise if only the latest space view or calibration look were used. The triangular smoothing window is about 100 scan lines long, centered on the current observation. NC1 is the smoothed value of the spectral radiance emitted by the black-body pertaining to the current observation.
4	$N = N1 + dN1_i,$	The radiance corrected for scan mirror and spectrometer polarization is N. dN1 is the polarization correction in NEN units. ai is the scan mirror angle, alpha is the angle of the major axis of the polarization ellipse of the spectrometer relative to the nadir view (ai=0), L1 is the spectral radiance emitted by the scan mirror surface at temperature T, pr is the scan mirror polarization at wavelength {i}, and pt is the spectrometer polarization at wavelength {i}. The index {i} loops over all wavelengths where pr * pt is larger than zero.

$$dN1_i := pr \cdot pt \frac{N1 \left[\cos\left[2\{a_i - alpha\}\right]\right] - \left\{1 - 2\frac{L1}{Nc1}\right\} \cos\{2 a_i\}\right] - L1\{1 + \cos\{2 a_i\}\}}{nen}$$

Table 3.1. Radiometric Calibration Algorithm.

3.2.2. Spectral Calibration Algorithm

1. Determination of the spectral sample centroids.

Information about the in-orbit spectral calibration of AIRS is obtained on every scan line (every 2.67 seconds) from the view of the spectral radiance from the target near nadir. We expect to obtain the mean position of six of the 12 arrays based on spectral features similar to the one shown in Figure 2.5. Based on the thermal characteristics of the focal plane material we assume that the detector pitch p and the relative position of the 12 arrays is given by the values determined in the ATCF. We assume that the grating constant d can be calculated from the grating constant d_o, measured empirically in the ATCF at grating temperature T_o, by adjusting it for the known thermal expansion coefficient of Aluminum. We thus have six equations to solve for 3 spectrometer model parameters: L, α, and Xo, using the least square residual formulation with the simplex algorithm.

No decision can be made about the validity of the spectral calibration based on analysis of data from one scan line. Based on the analysis of about 100 (TBD) spectral calibrations a decision is made if the observed values differ significantly from the currently used values. The first indication of the expected magnitude of shifts due to orbital thermal perturbations

comes from the 24 hour test in the ATCF. These statistics are refined based on experience during the first few months of the in-orbit checkout.

If L, α , and Xo differ insignificantly from the currently accepted values, then the current wavelength assignment for all spectral samples remains valid.

If L, α , and Xo differ significantly from the currently accepted values, then an assessment has to be made if the new values of L, α , and Xo have shifted within the statistically expected range of variations or if there is a larger shift.

If the shift is within the (TBD) acceptable range, then a new wavelength assignment is made for all detectors using the spectrometer equation

$\lambda_i = d/m * (\sin \alpha + \sin(atan((Xo+Xj +(i-1)*p_i)/L)))$.

If the shift is larger than the (TBD) acceptable range then an operator alert is issued to determine the cause and the use of the AMA has to be considered.

2. Shifting to the standard frequency set.

Major thermal or vibration disturbances, such as launch vibrations, gravity release, cold space view maneuvers or decontamination warm-ups in orbit may cause the spectrometer parameters L, α, and Xo to shift significantly from the values determined in the ATCF. The spectrometer is expected to stabilize within about 8 weeks after launch. The AMA will be used at that time to shift the collimator mirror, such that L, α, and Xo agree adequately with the values determined in the ATCF. The stable mean frequency set will be declared "the standard frequency set". All transmittances used by the retrieval algorithm will at that point be recalculated for the standard frequency set, using the closest SRF measured at each frequency.

The frequencies actually observed at any time are expected to oscillate slowly (at the orbital period) about the standard frequency values by a small fraction of Δv. The amplitude is analytically predicted to be less than $0.01*\Delta v$. The frequency shifting algorithm of the level 1b software shifts the spectral radiances from the true frequencies to the standard frequency set. To the level 2 software the AIRS channel frequencies are fixed. The shifting algorithm can handle frequency shifts of up to $0.05*\Delta v$ with acceptable accuracy.

The time series of L, α, and Xo determined from the in-orbit spectral calibration are input to the routine in-orbit calibration monitoring. Since L, α , and Xo also determine the active spectral frequency of the channels, there is no need to save 2500 frequencies.

3. Cloud effects.

If the field-of-view is partially cloudy, then the spectral contrast of some features decreases. If the contrast drops below a TBD level for more than half of the spectral features, the spectral algorithm calibration software skips to the next field-of-view. The spectral features in the 15 micron CO_2 band originate from the tropopause, which is too high for most clouds.

3.2.3. Geolocation

Determination of the absolute location of the AIRS spectrometer footprint on the ground to within 0.1 degree (1.5 km at nadir) is adequate. This accuracy is achieved from first principles calculations with the toolkit using the time/date and the known scan angle of the spectrometer and spacecraft attitude. The AIRS Vis/NIR Geolocation algorithm Document JPL ADF-265 describes a technique for using known surface features (such as islands) to determine the geolocation of the 0.16 degree Vis/NIR pixels to about 0.02 degree.

4. Preflight Validation

The operational data provided by AIRS, which is an EOS Facility Instrument, will support many scientific purposes, as indicated in the introduction.   Each purpose can be considered an independent experiment, requiring its own validation. AIRS provides imaged, spectro-radiometric data of the spectral radiance upwelling from the atmosphere. Validation of the accuracy of the radiometric, spectral and spatial data provided by AIRS is a part of the validation of the experiment.

4.1. Pre-flight Equipment Validation

4.1.1. Calibration Equipment Validation

The radiometric response of AIRS will be calibrated pre-flight in a vacuum chamber which reasonably simulates the on-orbit environment. The calibrating sources include a simulated cold space target, used to establish detector channel off-sets, and a variable temperature, large area blackbody source, used to calibrate the instrument responses above the oft-set levels. The accuracies of both sources are equally important to the accurate radiometric calibration of the instrument. The primary method of ensuring the accuracy of the sources is to measure (noting measurement error bars) the properties of the components making up the sources, and then by modeling and analysis, using the results of the measurements, show the performance of the source together with the error bars on the results. The radiometric accuracy required of the source is projected to be 1% over the range of wavelength and scene brightness temperatures applicable to AIRS. The important component parameters to measure include

(1) the spectral emissivity of the interior surfaces of the source cavity;
(2) the spectral BRDF of the interior surfaces of the source cavity;
(3) the temperature to resistance calibrations of the temperature sensors used to measure cavity temperatures; and
(4) the thermal conductivity of the materials comprising the cavity, including the blackening surface treatment applied to the emitting surfaces.

 Items (1) and (2) can be measured on ATCF components by independent service vendors. The comparison of the results obtained from more than one vendor will serve as a cross-check on the results. Coupon samples can also be submitted to NIST for measurement (anticipated schedule constraints prevent, in our baseline plan, the direct calibration and characterization by NIST of the large area and space view source assemblies). Item (3) can be measured by vendors with calibration facilities traceable to NIST.   The schedule and budget do not allow direct calibration of the flight temperature sensors by NIST. Item (4) can be measured in house and the results can be cross-checked against published values for corroboration. Only in the case that scheduling constraints permit, the completed units can be submitted to NIST for direct calibration. The flight radiometric calibration blackbody source will be calibrated after integration into the AIRS instrument against the large area blackbody in the ATCF. However, as schedule and resources permit, its accuracy through analysis of component characteristics obtained during its manufacture and check-out will similarly be treated. Inter comparison between the instrument response to the flight black body and the ATCF source when at the same temperature will then be a further validation of the radiometric calibration accuracy achieved.

The spectral calibrations of AIRS provided by the FT-IR spectrometer can be directly validated at selected wavelengths through the use of a gas cell, containing appropriate gasses at low pressure. Validation of the widths of the slit response functions measured with the FT-IR will be indirect using the end-to-end tests 9 and 10 described section 2.4.2.1.

The validity of the Bruker absolute spectral calibration will be established by measuring the transmission spectrum of a gas cell using the Bruker internal detector. The Bruker FTIR has resolution of 0.1 cm^{-1}, compared to the highest resolution of AIRS of 0.5cm^{-1}. The validation will occur using the FTS with a 1.6 degree FOV.

Spatial calibrations of the AIRS instrument map the instrument IFOV response, including low level responses at large off-axis angles (out of field of view response), measure the degree of simultaneity of IFOV response functions for all wavelengths (the parameter Cij), and establish the instrument boresight (i.e., the angular relationships between the centroid of the IFOV response function and the normals to reference optical flats affixed to the exterior of the instrument). The equipment used to perform these calibrations includes the collimating optics of the spatial collimator chamber and commercially obtained optical alignment tools, such as theodolites and autocollimators. These latter alignment tools will be furnished with certificates of calibration warranting accuracy to much better than AIRS calibration needs. Periodic calibration of these tools in accordance with Lockheed Martin calibration policy will ensure accuracies are maintained. The collimating optics in the spatial collimator chamber will be initially well characterized under operating conditions (in vacuum) prior to use with AIRS and will be periodically re-characterized to ensure measurement accuracies remain within requirements. All tools used in the characterizations will themselves bear current calibrations.

The Vis/NIR subsystem radiometric response calibrations need not be accurate in an absolute sense but only in a relative sense. Nevertheless, the calibration must be sufficiently accurate so that the response on-orbit remains within dynamic range limits. It is also necessary to establish the linearity of response during ground calibrations. Both these objectives can be met by devising diffuse radiance sources which are monitored in spectral radiance with commercially obtained visible band spectral radiometers. These radiometers come with certificates of accuracy traceable to NIST standards and will be periodically calibrated in accordance with Lockheed Martin policy to ensure the accuracy is maintained. The Vis/NIR spectral calibrations will be initially established by numerically multiplying the vendor furnished spectral response of the detectors and spectral transmittance of the bandpass filters, and in-house measurements of the spectral transmittances of the elements in the subsystem optical train. The spectral responses then can be validated by examining the ratios of the signals among the four bands as functions of the color temperature of the diffuse illumination from the calibrating source.

Spatial calibration of the Vis/NIR subsystem in terms of mapping of its IFOV, simultaneity of IFOV response in all four bands and boresight will be established using the same spatial collimator chamber (adapted with a visible source) and associated alignment tools as used to calibrate the IR spectrometer portion of AIRS. The same validations in the IR of the spatial collimator chamber components also serve to validate its performance in obtaining the Vis/NIR spatial calibrations.

4.1.2. Calibration - Analytic Validation

As the AIRS instrument is assembled and integrated, an extensive series of component, assembly and subsystem calibrations is performed which, through analysis and comparison with the results of higher level characterizations, serve to validate those higher level measurements and the calibrations made at the instrument level. The focal plane detector arrays and read-out integrated circuits are extensively characterized in terms of radiometric and spectral response and geometric layout of the arrays. The grating and its associated optics, the scanning and beam dividing optics, and the flight calibration sources will be evaluated separately as well as in conjunction with other system components. Each entrance aperture and focal plane order-separation filter will be measured separately, either by their manufacturers or an independent vendor. The focal plane filters will be mounted on the detector arrays and the combined detector/filter spectral responses will be evaluated. Optical throughput and alignment measurements will be made. Similarly, the

scan subsystem and its components will be fully characterized before integration the remainder of the instrument subsystems.

The AIRS computer models, as described in Section 3, also serve to validate calibration results. These models will be updated with component and assembly data as they become available. They will be the essential tools for analytically predicting the performances of higher level assemblies based on measurements made on components and sub-assemblies.

4.1.3. End-to-end pre-flight validation.

Ideally, one would want to use the AIRS instrument as a sounder, perhaps mounted in a balloon or aircraft, before the instrument is launched into orbit, to obtain true end-to-end performance verification. The next best, and feasible tests are those planned and discussed in section 2.4.2.1. tests 9 and 10. The setup of the test and taking of the test data is the hardware contractor's responsibility. Analysis of the test results is an AIRS science team member responsibility.

4.2. EOS/NIST Cross-Calibration Effort

The EOS Project has explored with NIST the development of portable radiometric calibration equipment that can be taken to each instrument vendor in order to verify the radiometric calibrations of all EOS instruments. No funding has been made available to accommodate such cross calibration efforts.

5. In-flight Calibration Validation

Validation of the calibration in-flight is carried out along two paths: Consistency of the calibration parameters and instrument indicators with the conditions in the ATCF, and comparison with natural sources and other instruments on the EOS PM spacecraft. These activities are described in the AIRS Validation Plan, submitted to the EOS project office at GSFC on 15 September 1997. A summary is provided here.

5.1. Consistency

Consistency of the calibration parameters and instrument indicators with the conditions in the ATCF is the responsibility of the calibration team at the TLSCF. This is a indirect indicator, since some expected changes to the validity of the calibration may occur even if all engineering indicators indicate a normal functioning instrument. For example, changes due to prolonged radiation exposure may cause a change in the non-linearity of the signal chain, or in the calibration of a temperature sensor. Such effects are picked up by the routine comparisons between the global colocated radiosonde and surface buoys.

5.2. Comparison with natural sources

Comparison with natural sources, ground campaigns and comparison with other instruments in selected areas will be a means of indirectly validating the AIRS calibration. The in-flight validation of the calibration will be the responsibility of the science team.

5.2.1. Spectral Validation with natural sources: By design the AIRS spectral calibration is routinely monitored (and adjusted) relative to the upwelling spectral radiance. Stability in the spectrometer model parameters and the value of the peak cross-correlation are indications of the spectral calibration validity.

5.2.2. Radiometric Validation:

5.2.2.1. Routine Validation: Selected   AIRS surface channel brightness temperatures, particularly at 2616 cm^{-1} during night time, corrected for the atmospheric transmittance, will be routinely compared to the surface buoy network reported temperatures and from colocated radio sonde network. Of the 12 AIRS arrays, 9 arrays include one or more surface channels which are not directly coincident with a water or other minor gas absorption line. Most of these channels need to be corrected for water continuum, with brightness temperature correction as large as 15 degrees. By design, if one channel in an AIRS array is properly calibrated, then all channels in that array are calibrated.

5.2.2.2. Spot testing: Planned activities include validation using ground-truth, vicarious calibration for the Vis/NIR channels, Aircraft underflights, and cross-calibration with MODIS and CERES. As details of the spectral and spatial response functions and the absolute calibration accuracies of these instruments become available, and the AIRS performance is established during the pre-launch calibration, the expected agreement of cross-calibration can be estimated.

6. End-to-End Calibration Accuracy

The required accuracies for the radiometric, spectral, spatial and photometric calibrations of AIRS of sources of the various calibration elements flow from the FRD overall requirements.
The ground-based calibration algorithms do not limit the accuracy of the calibration achieved pre-launch.

6.1. Radiometric Accuracy. The FRD specifies the total radiometric calibration error as not to exceed 3% of the scene radiance or 4*NEN, whichever is larger. The four main groups of error are: Non-linearity errors, Offset related errors, Gain/offset coupled scan angle dependent effects, and Flight calibrators radiance errors. Appendix A summarizes projections of absolute radiometric accuracy as fraction of the scene radiance, showing the contributions to the error from all expected sources at four representative wavelengths, $3.7\mu m$, $4.2\mu m$, $8.22\mu m$ and $15\mu m$, at the brightness temperatures typical for these wavelengths, 258K, 250K, 240K and 231K, respectively, after 5 years in orbit. Left margin indentations indicate error components which are combined root-sum-squared. The absolute calibration requirement of 3% of the scene radiance is satisfied at all wavelengths. The main source of calibration error, ADC differential non-linearity at the shortest wavelength, and readout-non-linearity at the longer wavelengths, does not exits at the start of the mission: It is due to long term changes in the electronics due to natural radiation environment in orbit.

6.2. Spectral Calibration Accuracy. The FRD specifies that for all the 2500 AIRS spectral channels, the   spectral response function (slit response functions, SRF), loosely characterized as the full width at half maximum (FWHM) of the SRF, and the position of the centroid of the SRF, i.e. the absolute wavelength knowledge. The FWHM has to be measured with 1% accuracy, and the centroid of each SRF has to be measured with an accuracy of 1% of the FWHM. The SRF wing response has to be known down to a level of 1/3000 relative to the peak SRF response.

The spectral calibration error can be divided into three components: Ground-Software On-Orbit Correction, On-Orbit Stability between calibration updates, and Prelaunch Ground Calibration. Tables 2.3. and Table 2.4. summarize calibration error budgets for the SRF centroid and FWHM in three characteristic wavelength regions. The spectral calibration budget for the SRF centroid and FWHM can be met for all channels (before the start of the Engineering Model testing). Issues, like run time optimization and the need for the integrating sphere will be explored during testing with the engineering module.

6.3. Spatial Calibration Accuracy. Although all AIRS channels share the same field stop, diffraction and vignetting produce spatial differences in the field-of-view response function as a function of wavelength. The FRD specifies three spatial calibration related parameters:
a)   the field of view, nominally 1.1 degree (FWHM) diameter has to be known to 10% accuracy.
b)   the wing response in a 2.5 degree cone diameter down to a 0.01 level.
c)   the relative superposition accuracy of the field of view of all wavelengths. The FRD states the co-alignment requirement as 99%, and mathematically states this requirement in terms of the C_{ij} parameter, where (i) and (j) refer to the spatial response from the i-th and j-th spectral sample.

The spatial calibration accuracy requirements a) and b) are easily met at all wavelength. The definition of C_{ij} (2.4.2.1. paragraph 8) uses an absolute value, i.e. noise is rectified. This makes its determination very sensitive to SNR. A measurement of C_{ji} to within 2% can be accomplished in under one hour. A measurement with 0.5% accuracy needed to demonstrate FRD compliance with the 99% specification will be time consuming. This issue will be explored with the engineering model.

Appendix A: PRELIMINARY RADIOMETRIC ERROR PROJECTIONS

The following chart summarizes projections of absolute radiometric accuracy as fraction of the scene radiance, showing the contributions to the error from all expected sources at four representative wavelengths, 3.7μm, 4.2μm, 8.22μm and 15μm, at the brightness temperatures typical for these wavelengths, 258K, 250K, 240K and 231K, respectively, after 5 years in orbit. The absolute calibration requirement of 3% of the scene radiance is satisfied at all wavelengths. The main source of calibration error, ADC differential non-linearity at the shortest wavelength, and readout-non-linearity at the longer wavelengths, does not exits at the start of the mission: It is due to long term changes in the electronics due to natural radiation environment in orbit. The four main groups of error are: Non-linearity errors, Offset related errors, Gain/offset coupled scan angle dependent effects, and Flight calibrators radiance errors. Left margin indentations indicate error components which are combined root-sum-squared.

Source	Predicted Errors for Four Wavelengths (μm)				Required Values	
	D1a min	D1b mid	D4d max	D12 mid		
	3.7364	4.2	8.22	15	Value	Units
Total Radiometric Error	0.0245	0.0189	0.0222	0.0293	0.0300	fraction of Nscene
Non-Linearity Errors	0.0221	0.0156	0.0197	0.0270	0.0175	fraction of Nscene
Residual Non-Linearity Calibration Error	0.0003	0.0015	0.0191	0.0268	0.0175	fraction of Nscene
Re-Calibration On-Orbit	0.0001	0.0009	0.0146	0.0207	0.0207	fraction of Nscene
Variabl Integration Time Calibration	0.0001	0.0009	0.0144	0.0204	0.7130	fraction of Nmax_scene
Noise in Re-Calibration Measurements	0.0001	0.0001	0.0024	0.0034	0.5000	specNEDT
Non-Linearity Drift Between Re-Calibrations	0.0003	0.0012	0.0123	0.0171	0.0171	fraction of Nscene
Focal Plane (Detectors and ROICs)	0.0001	0.0006	0.0101	0.0143	0.4991	fraction of Nmax_scene
Sensor Electronics	0.0003	0.0010	0.0071	0.0094	0.0077	fraction of Nscene
Un-Calibratable Non-Linearities	0.0221	0.0155	0.0049	0.0028	0.3798	specNEDT
A/D Converter Integral Non-Linearity	0.0062	0.0094	0.0042	0.0025	1.7500	LSB
A/D Converter Differential Non-Linearity	0.0212	0.0123	0.0025	0.0014	1.0000	LSB
Offset Related Errors	0.0025	0.0026	0.0013	0.0105	0.0105	fraction of Nscene
Background/Leakage Curr. Fluctuations	0.0005	0.0004	0.0007	0.0104	1.3905	specNEDT
Space Look Subtraction Processing	0.0005	0.0004	0.0007	0.0104		---
Time scale for fluctuations	0.0005	0.0004	0.0007	0.0104	~6300	seconds
FPA Temp.	0.0001	0.0001	0.0001	0.0083	1.2001	K, 0 to pk.
Optics Temp.	0.0001	0.0001	0.0004	0.0001	10.4002	K, 0 to pk.
Scan Mirror Temp.	0.0005	0.0004	0.0002	0.0001	15.2500	K, 0 to pk.
Chopper Temp.	0.0001	0.0001	0.0001	0.0018	110.1200	K, 0 to pk.
Scan Assembly Non-Uniformities	0.0016	0.0020	0.0007	0.0003	0.0406	specNEDT
Mirror Temp. Gradients	0.0012	0.0015	0.0006	0.0002	0.1000	K/diameter, rms
Baffle Temp. Gradients	0.0004	0.0004	0.0002	0.0001	3.0000	K/diameter, rms
Baffle Emiss. Variations	0.0001	0.0001	0.0001	0.0001	0.0333	emissivity, rms
Space Look Errors	0.0017	0.0015	0.0007	0.0004	0.0898	specNEDT
Out of Field Earth Background	0.0009	0.0007	0.0002	0.0001	0.0005	specNEDT
Out of Field Earth Shield Background	0.0014	0.0013	0.0007	0.0004	0.0898	specNEDT
Gain / Offset Scan Angle Dependent Effects	0.0051	0.0067	0.0089	0.0028	0.0024	fraction of Nscene
Film Emiss. Variations	0.0025	0.0036	0.0025	0.0016	0.0003	emissivity, rms
Particle Emiss. Variations	0.0016	0.0024	0.0016	0.0010	0.0002	emissivity, rms
Clean Surface Emissivity Variations	0.0023	0.0033	0.0022	0.0014	0.0003	emissivity, rms
Initial Calibration, Gain Term	0.0032	0.0035	0.0015	0.0014	0.0005	Ncal
Scan Angle Calibr. & Polarization	0.0014	0.0017	0.0080	0.0008	0.1015	specNEDT

Source (continued)	Predicted Errors for Four Wavelengths (µm)				Required Values	
	D1a min	D1b mid	D4d max	D12 mid		
	3.7364	4.2	8.22	15	Value	Units
Flight Calibrator Radiance Error	0.0088	0.0080	0.0048	0.0035	0.0035	fraction of Ncal
Temperature Knowledge Error	0.0072	0.0064	0.0033	0.0019	0.1774	K
Device Calibration	0.0045	0.0040	0.0021	0.0012	0.1118	K
Modeled Surface to Bulk Temp. Accuracy	0.0012	0.0011	0.0006	0.0003	0.0300	K
Modeled Bulk to Device Temp. Accuracy	0.0016	0.0014	0.0007	0.0004	1.0400	K
Modeled Area Average Temp. Accuracy	0.0020	0.0018	0.0009	0.0005	3.5067	K
Device Self Heating Uncertainty Error	0.0024	0.0022	0.0011	0.0006	3.0600	K
Power Dissipation in Device	0.0024	0.0022	0.0011	0.0006	4.0002	Watt
Electronic Readout Accuracy	0.0048	0.0043	0.0022	0.0013	5.1184	K
Device Resistance Meas. Accuracy	0.0048	0.0043	0.0022	0.0013	6.0042	% resistance
Emissivity Knowledge Error	0.0022	0.0021	0.0015	0.0010	7.0010	emissivity
Reflected Background Radiation	0.0022	0.0021	0.0014	0.0009	8.3621	specNEDT
Cavity Wedge Angle	0.0001	0.0001	0.0001	0.0001	32.2000	degrees
Surface Specular Reflectance	0.0001	0.0001	0.0001	0.0001	10.1400	---
Degradation with life	0.0001	0.0001	0.0001	0.0001	11.0700	---
Surface BRDF at large angles	0.0003	0.0003	0.0002	0.0001	0.0003	sr^-1
Degradation with Life	0.0018	0.0017	0.0012	0.0008	0.0020	sr^-1
Degradation with contamination	0.0001	0.0001	0.0001	0.0001	0.0002	sr^-1
Contamination Level	0.0001	0.0001	0.0001	0.0001	450.0000	LEVEL
View Solid Angle	0.0022	0.0021	0.0014	0.0009	1.1331	sr
IFOV Underfill	0.0006	0.0006	0.0004	0.0002	0.0945	specNEDT
Minimum Cone Angle from Entr. Aperture	0.0005	0.0005	0.0003	0.0002	1.6000	degrees
Reserve (e.g., Chamber BB to Flight Cal)	0.0025	0.0025	0.0025	0.0025	0.0025	fraction of Ncal
Accuracy of Chamber BB	0.0030	0.0027	0.0014	0.0008	0.0008	fraction of Ncal
Temperature Knowledge Error	0.0030	0.0027	0.0014	0.0008	0.0735	K
Device Calibration	0.0008	0.0007	0.0004	0.0002	0.0200	K
Modeled Surface to Bulk Temp. Accuracy	0.0012	0.0011	0.0006	0.0003	0.0300	K
Modeled Bulk to Device Temp. Accuracy	0.0012	0.0011	0.0006	0.0003	0.0300	K
Modeled Area Average Temp. Accuracy	0.0020	0.0018	0.0009	0.0005	0.0500	K
Device Self Heating Uncertainty Error	0.0014	0.0012	0.0006	0.0004	0.0333	K
Power Dissipation in Device	0.0014	0.0012	0.0006	0.0004	0.0001	Watt
Electronic Readout Accuracy	0.0006	0.0005	0.0003	0.0001	0.0140	K
Device Resistance Meas. Accuracy	0.0006	0.0005	0.0003	0.0001	0.0005	fraction of resist.
Emissivity Knowledge Error	0.0001	0.0001	0.0001	0.0001	0.0000	emissivity
Reflected Background Radiation	0.0001	0.0001	0.0001	0.0001	0.0025	specNEDT
Cavity Wedge Angle	0.0001	0.0001	0.0001	0.0001	25.7000	degrees
Surface Specular Reflectance	0.0001	0.0001	0.0001	0.0001	0.1400	---
Degradation with life	0.0001	0.0001	0.0001	0.0001	0.0200	---
Surface BRDF at large angles	0.0001	0.0001	0.0001	0.0001	0.0003	sr^-1
Degradation with Life	0.0001	0.0001	0.0001	0.0001	0.0002	sr^-1
Degradation with contamination	0.0001	0.0001	0.0001	0.0001	0.0000	sr^-1
Contamination Level	0.0001	0.0001	0.0001	0.0001	350.0000	LEVEL
View Solid Angle	0.0001	0.0001	0.0001	0.0001	0.0676	sr
IFOV Underfill	0.0001	0.0001	0.0001	0.0001	0.0264	specNEDT
Minimum Full Cone Angle to Entr. Aperture	0.0001	0.0001	0.0001	0.0001	2.5000	degrees
Reflectance of External Lip	0.0001	0.0001	0.0001	0.0001	0.0500	---
Scene Temperature for computed errors	258.327	250.418	240.03	231.522		K

Appendix B: DEFINITION OF TERMS

Accuracy: The deviation between the result of a measurement and the true value of the measurand. This true value is defined (or closely approximated) through use of a physical standard.

Algorithm: A defined subroutine, program or set of instructions, analytical expressions1 limits or specifications for estimating or retrieving an observed physical quantity from measurement data obtained by an instrument.

Calibration: The set of operations which establish, under specified conditions, the relationship between values indicated by a measuring instrument and the corresponding known values of a physical standard.

Cross-calibration: The process of assessing relative accuracy and/or precision of response of two or more instruments to the same input source.

Data Products: Defined categories of data classification and categorized measured and derived physical parameters. This includes both standard products (those produced by routine processing at the EOSDIS) and specialized products (produced by Science Team members at their home institutions).

Drift: The slow variation with time of an instrument parameter that affects or appears in an output.

Dwell Time: The integration time during spatial viewing in which a given measurement is obtained for a defined spatial resolution element (see IFOV and pixel).

Echelle Grating: A relatively coarse grating with steeper groove planes than standard grating types, originally developed by G. R. Harrison (1953) for working in moderate orders, e.g., 3-15 in the AIRS conceptual design. Band limiting filters are used here to separate overlapping orders.

Fiducial Reference: The angular orientation reference relative to the defined boresight of a remote sensing system that allows it to be aligned to other instruments and structures.

Instantaneous Field of View (IFOV): The two-dimensional angular field locus that is viewed by an instrument at any given instant in time.

Instrument model: A mathematical description of a sensor system relating simulated inputs to computed outputs, considered here as a computer program. To be useful, it must be sufficiently detailed to provide meaningful data to system analysis studies, such as performance prediction, uncertainty (or error) modeling, and isolation of failure or degradation mechanisms.

Order (Diffraction Grating): If a collimated monochromatic beam of radiation is reflected from a diffraction grating, the emergent rays that are reflected at an angle equal to the angle of incidence of the radiation from the flat plane of the grating are considered to fall in the zero spectral order. Diffraction from the grooved grating
surface causes the rays to form a series of maxima at other angles of reflection relative to the zero order reflection angle. The angular spacing of these maxima depends on resulting alignments in the wavefronts exiting from each grating facet. The number of wavelengths of offset between adjacent facet wavefronts that reinforce each other is the order of each maximum.

Physical Standard: An accepted material, instrument, procedure, or system to be used as a reference for establishing or closely approximating the true value of a physical quantity or unit.

Primary Standard: A standard which defines or approximates a defined metrological quality as closely as possible. In the USA, primary standards are provided at the National Institute of Standards and Technology (NIST). Secondary Standard: A standard whose value is fixed by comparison with a primary standard. Tertiary Standard: A standard whose value is fixed by comparison with a secondary standard.

Pixel: The smallest spatial resolution element that is resolved by a remote sensing instrument, within which the total radiance is integrated and determined for the applicable dwell time as an instrumental output. A single pixel generally corresponds to the IFOV of the instrument. A pixel is not to be confused with spatial resolution.

Precision: The repeatability of measurements made with the same sensor of the same input source.

Resolution: A quantitative expression of the ability of an instrument to distinguish between the smallest detectable values of the input quantity measured, based on some definition, such as the Rayleigh criterion.

Resolving Power: The ratio between a wavelength (or wavenumber) measured by a spectrometer and its spectral resolution at that wavelength in the same units.

Response Time: The time interval between the instant when an input exhibits a specified abrupt (step) change and the instant when the instrument output reaches a selected fraction (sometimes 0.99) of its final value. A response time to $1-1/e = 0.632$ of final value is termed the time constant of a single stage (pole) electrical filter.

Responsivity: Change in the output of a detector, subsystem, or instrument divided by a corresponding change in input stimulus. DC Responsivity: Total change in output divided by the corresponding change in input from zero to some level. AC Responsivity: Net change in output divided by the corresponding net change in input, regardless of static output and input levels.

Sensitivity: The minimum detectable change in the response of a measuring instrument produced by a change in the input stimulus, usually defined at a given offset level of stimulus.

Noise-Equivalent Sensitivity: The change in the response of a measuring instrument produced by a change in the stimulus which is equal to the instrument's measurement noise, usually in terms of the peak-to-peak input stimulus and the root-mean-squared (rms) noise.

Spatial Resolution: The spatial resolution is given approximately twice the spatial sampling step size. If the IFOV diameter (here defined as the boundary enclosing 50% of the peak radiance from a point source) is less than twice the sampling step size, than the spatial aliasing occurs.

Spectral Band: The range of spectral radiation input to which a channel of a sensor produces significant output.

Spectral Resolution: That wavelength (wavenumber) interval that a spectrometer can distinguish from an adjacent interval, here considered as the full-width half-maximum (FWHM) slit response function, expressed in terms of power, radiance or irradiance.

Stability: The ability of an   instrument to maintain constant its metrological characteristics. Generally a measure of variation in response to a known stable input source.

Traceability: The description of a measurement which relates it to physical standards by an unbroken chain of comparisons.

Validation: The process of assessing the import and accuracy of physical measurements derived from the output of the instrument. This is done by analysis of the self-consistency of the sensor output in terms of other internal and external measurements by the same instrument and by inter-comparison with data products
from other sensors.

Verification: The process of test and analysis to be performed during the design, development, assembly and integration phases of an instrument to assure all instrument functional requirements have been met.

Appendix C: LIST OF ABBREVIATIONS AND ACRONYMS

A   Angstrom = 10^{-8} meter
ADC   Analog to Digital Converter
AIRI   Atmospheric Infrared Interferometer (used for validation)
AIRS   Atmospheric Infrared Sounder
AMA   Adjustable Mirror Assembly
ARM   Atmospheric Radiation Monitoring site (used for
ATBD   validation)
ATCF   Algorithm Theoretical Basis Document
BCE   AIRS Test and Calibration Facility
                           Bench Checkout Equipment

BOMEM
BRDF   Company which built the spatial collimator, LABB and
CDR   SVBB
cm   Bi-directional Reflectance Distribution Function
CO   Critical Design Review
$C0_2$ centimeters
                           carbon monoxide
$\Delta\lambda$ carbon dioxide
EOS
EOSDIS   width of spectral resolution element; spectral resolution
FPA   Earth Observing System
FRD   EOS Data and Information System
FTS, FT-IR   Focal Plane Array
                           AIRS Functional Requirements Document, JPL D-8236
FOV   Fourier Transform - Infrared Spectrometer
FWHM
GSE   Field of View
GSFC   Full Width at Half Maximum of the SRF
GSS   Ground Support Equipment
HgCdTe   Goddard Space Flight Center
IFOV   Ground Support Station
IFG   Mercury Cadmium Telluride
                           Instantaneous Field of View
IR   Interferogram
JPL
K   Infrared
KBr   Jet Propulsion Laboratory/California Institute of
kg   Technology
LABB   Kelvin
LIRIS   Calcium Bromide, infrared window material
                           kilogram
Mb/s   Large Area Blackbody, radiometric calibration source
MLI   LM Infrared and Imaging Systems, Inc.
mm
MODIS   Mega-bits/second
μ Multi-Layer Insulation
N_2 millimeters
                           Moderate Resolution Infrared Spectrometer
                           10^{-6} meter
                           nitrogen

LIST OF ABBREVIATIONS AND ACRONYMS, cont.

NASA	National Aeronautics and Space Administration
NEN	Noise Equivalent Radiance
NEΔT	Noise Equivalent Temperature Difference
NH_3	Ammonia
NIR	Near Infrared
NIST	National Institute of Standards and Technology
OPD	Optical Path Difference (sets resolution of an FTS)
PDR	Preliminary Design Review
PM	after noon
PRT	Platinum Resistance Thermometer
PV	Photo Voltaic
ROS	Reference Optical Surface
RSS	root sum squared
σ	standard deviation
SNR	Signal to Noise Ratio
sr	steradian, units of solid angle
SRF	Spectral Response Function
SVBB	Space View Blackbody cold reference source
TBD	To Be Determined
TBR	To Be Reviewed
TLSCF	Team Leader Science Computing Facility (responsible for calibration software delivery to EOSDIS)
TQCM	Temperature-controlled Quartz Crystal Microbalance
TVC	Thermal Vacuum Chamber
Vis/NIR	Visible/Near Infrared
W	Watt
ZPD	Zero Path Difference (Michelson Interferometer)
μm	micrometer